PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference 893 pct	FOR FURTHER ACTION	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
International application No. PCT/SE00/00034	International filing date *(day/month/year)* 12-01-2000	Priority date *(day/month/year)* 18-01-1999
International Patent Classification (IPC) or national classification and IPC7 G05D 1/08		
Applicant SAAB AB et al		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 3 sheets, including this cover sheet.

   ☐ This report is also accompanied by ANNEXES, i.e., sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of ______ sheets.

3. This report contains indications relating to the following items:

   - I ☒ Basis of the report
   - II ☐ Priority
   - III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - IV ☐ Lack of unity of invention
   - V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
   - VI ☐ Certain documents cited
   - VII ☐ Certain defects in the international application
   - VIII ☐ Certain observations on the international application

Date of submission of the demand	Date of completion of this report
29.06.2000	26.03.2001
Name and mailing address of the IPEA/SE Patent- och registreringsverket Box 5055 S-102 42 STOCKHOLM Telex 17978 PATOREG-S Facsimile No. 08-667 72 88	Authorized officer Lars Jakobsson /itw Telephone No. 08-782 25 00

I. Basis of the report

1. With regard to the **elements** of the international application:*

☒ the international application as originally filed

☐ the description:
pages ______________________________, as originally filed
pages ______________________________, filed with the demand
pages ______________________________, filed with the letter of ______________

☐ the claims:
pages ______________________________, as originally filed
pages ______________________________, as amended (together with any statement) under article 19
pages ______________________________, filed with the demand
pages ______________________________, filed with the letter of ______________

☐ the drawings:
pages ______________________________, as originally filed
pages ______________________________, filed with the demand
pages ______________________________, filed with the letter of ______________

☐ the sequence listing part of the description:
pages ______________________________, as originally filed
pages ______________________________, filed with the demand
pages ______________________________, filed with the letter of ______________

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.
These elements were available or furnished to this Authority in the following language ______________ which is:

☐ the language of a translation furnished for the purposes of international search (under Rule 23.1(b)).
☐ the language of publication of the international application (under Rule 48.3(b)).
☐ the language of the translation furnished for the purposes of international preliminary examination (under Rules 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

☐ contained in the international application in written form.
☐ filed together with the international application in computer readable form.
☐ furnished subsequently to this Authority in written form.
☐ furnished subsequently to this Authority in computer readable form.
☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.

4. ☐ The amendments have resulted in the cancellation of:

☐ the description, pages ______________
☐ the claims, Nos. ______________
☐ the drawings, sheet/fig ______________

5. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2 (c)).**

* *Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are annexed to this report since they do not contain amendments (Rules 70.16 and 70.17).*

** *Any replacement sheet containing such amendments must be referred to under item I and annexed to this report.*

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.
PCT/SE00/00034

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Claims	1-24	YES
	Claims		NO
Inventive step (IS)	Claims	1-24	YES
	Claims		NO
Industrial applicability (IA)	Claims	1-24	YES
	Claims		NO

2. Citations and explanations (Rule 70.7)

The claimed invention relates to a method and an arrangement for synthetically calculating redundant attitude for an aircraft when the heading of the aircraft is known. The claimed invention also relates to a method for synthetically calculating redundant attitude and redundant heading for an aircraft with the aid of data existing in the aircraft. When the heading is available, attitude is calculated on the basis of the aircraft-fixed angular rates and the calculated attitude is corrected by means of air data and heading.

When the heading is not available attitude and heading are calculated on the basis of the body-frame angular rates and errors in the measured body-frame magnetic field vector components are estimated. The measured body-frame field magnetic field vector is derived. Errors in calculated attitude and heading are estimated with the aid of air data and derived measured body- frame magnetic field vector components. The calculated attitude and heading are corrected by means of estimated errors in attitude and heading.

Documents cited in the International Search Report:

US 4914598
US 5841537
WO 9726553

None of the documents describe a method and an arrangement for synthetically calculating redundant attitude and redundant heading by means of data existing in an aircraft as specified in the claims.

The claimed invention is considered to fulfil the requirements of novelty (N), inventive step (IS) and industrial applicability (IA).

RECORD COPY

PCT

REQUEST

The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty.

For receiving Office use only

PCT/SE 00/00034

International Application No. 09/889311

12 -01- 2000

International Filing Date

The Swedish Patent Office
PCT International Application

Name of receiving Office and "PCT International Application"

Applicant's or agent's file reference *(if desired) (12 characters maximum)* 893 PCT

Box No. I TITLE OF INVENTION

AUXILIARY SYSTEM IN AN AIRCRAFT FOR INDICATING ATTITUDE AND HEADING

Box No. II APPLICANT

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

SAAB AB
SE-581 88 LINKÖPING
SWEDEN

☐ This person is also inventor.

Telephone No. 013-18 00 00

Facsimile No. 013-18 71 95

Teleprinter No.

State *(that is, country)* of nationality: Sweden

State *(that is, country)* of residence: Sweden

This person is applicant for the purposes of: ☐ all designated States ☒ all designated States except the United States of America ☐ the United States of America only ☐ the States indicated in the Supplemental Box

Box No. III FURTHER APPLICANT(S) AND/OR (FURTHER) INVENTOR(S)

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

Adebjörk, Peter
Gryningsgatan 73
SE-589 29 LINKÖPING
Sweden

This person is:

☐ applicant only

☒ applicant and inventor

☐ inventor only *(If this check-box is marked, do not fill in below.)*

State *(that is, country)* of nationality: Sweden

State *(that is, country)* of residence: Sweden

This person is applicant for the purposes of: ☐ all designated States ☐ all designated States except the United States of America ☒ the United States of America only ☐ the States indicated in the Supplemental Box

☒ Further applicants and/or (further) inventors are indicated on a continuation sheet.

Box No. IV AGENT OR COMMON REPRESENTATIVE; OR ADDRESS FOR CORRESPONDENCE

The person identified below ~~is hereby~~/has been appointed to act on behalf of the applicant(s) before the competent International Authorities as: ☒ agent ☐ common representative

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country.)*

Lundmark, Jan-Erik
SAAB AB
Patent Department
SE-581 88 LINKÖPING
Sweden

Telephone No. 013-18 71 97

Facsimile No. 013-18 71 95

Teleprinter No.

☐ **Address for correspondence:** Mark this check-box where no agent or common representative is/has been appointed and the space above is used instead to indicate a special address to which correspondence should be sent.

Continuation of Box No. III FURTHER APPLICANT(S) AND/OR (FURTHER) INVENTOR(S)

If none of the following sub-boxes is used, this sheet should not be included in the request.

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

Nordlund, Per-Johan
Vretagatan 17
SE-582 37 LINKÖPING
Sweden

This person is:
- [ ] applicant only
- [x] applicant and inventor
- [ ] inventor only *(If this check-box is marked, do not fill in below.)*

State *(that is, country)* of nationality: Sweden

State *(that is, country)* of residence: Sweden

This person is applicant for the purposes of:
- [ ] all designated States
- [ ] all designated States except the United States of America
- [x] the United States of America only
- [ ] the States indicated in the Supplemental Box

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

Carlsson, Carl-Olof
Skogslyckegatan 11 D
SE-587 27 LINKÖPING
Sweden

This person is:
- [ ] applicant only
- [x] applicant and inventor
- [ ] inventor only *(If this check-box is marked, do not fill in below.)*

RO/SE

State *(that is, country)* of nationality: SE

State *(that is, country)* of residence: SE

This person is applicant for the purposes of:
- [ ] all designated States
- [ ] all designated States except the United States of America
- [x] the United States of America only
- [ ] the States indicated in the Supplemental Box

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

This person is:
- [ ] applicant only
- [ ] applicant and inventor
- [ ] inventor only *(If this check-box is marked, do not fill in below.)*

State *(that is, country)* of nationality:

State *(that is, country)* of residence:

This person is applicant for the purposes of:
- [ ] all designated States
- [ ] all designated States except the United States of America
- [ ] the United States of America only
- [ ] the States indicated in the Supplemental Box

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

This person is:
- [ ] applicant only
- [ ] applicant and inventor
- [ ] inventor only *(If this check-box is marked, do not fill in below.)*

State *(that is, country)* of nationality:

State *(that is, country)* of residence:

This person is applicant for the purposes of:
- [ ] all designated States
- [ ] all designated States except the United States of America
- [ ] the United States of America only
- [ ] the States indicated in the Supplemental Box

- [ ] Further applicants and/or (further) inventors are indicated on another continuation sheet.

Box No.V DESIGNATION OF STATES

The following designations are hereby made under Rule 4.9(a) *(mark the applicable check-boxes: at least one must be marked)*:

Regional Patent

- [ ] **AP** **ARIPO Patent:** **GH** Ghana, **GM** Gambia, **KE** Kenya, **LS** Lesotho, **MW** Malawi, **SD** Sudan, **SL** Sierra Leone, **SZ** Swaziland, **UG** Uganda, **ZW** Zimbabwe, and any other State which is a Contracting State of the Harare Protocol and of the PCT
- [ ] **EA** **Eurasian Patent:** **AM** Armenia, **AZ** Azerbaijan, **BY** Belarus, **KG** Kyrgyzstan, **KZ** Kazakhstan, **MD** Republic of Moldova, **RU** Russian Federation, **TJ** Tajikistan, **TM** Turkmenistan, and any other State which is a Contracting State of the Eurasian Patent Convention and of the PCT
- [X] **EP** **European Patent:** **AT** Austria, **BE** Belgium, **CH and LI** Switzerland and Liechtenstein, **CY** Cyprus, **DE** Germany, **DK** Denmark, **ES** Spain, **FI** Finland, **FR** France, **GB** United Kingdom, **GR** Greece, **IE** Ireland, **IT** Italy, **LU** Luxembourg, **MC** Monaco, **NL** Netherlands, **PT** Portugal, **SE** Sweden, and any other State which is a Contracting State of the European Patent Convention and of the PCT
- [ ] **OA** **OAPI Patent:** **BF** Burkina Faso, **BJ** Benin, **CF** Central African Republic, **CG** Congo, **CI** Côte d'Ivoire, **CM** Cameroon, **GA** Gabon, **GN** Guinea, **GW** Guinea-Bissau, **ML** Mali, **MR** Mauritania, **NE** Niger, **SN** Senegal, **TD** Chad, **TG** Togo, and any other State which is a member State of OAPI and a Contracting State of the PCT *(if other kind of protection or treatment desired, specify on dotted line)* ....

National Patent *(if other kind of protection or treatment desired, specify on dotted line)*:

- [ ] **AE** United Arab Emirates
- [ ] **AL** Albania ....
- [ ] **AM** Armenia ....
- [ ] **AT** Austria ....
- [X] **AU** Australia ....
- [ ] **AZ** Azerbaijan
- [ ] **BA** Bosnia and Herzegovina ....
- [ ] **BB** Barbados
- [ ] **BG** Bulgaria ....
- [X] **BR** Brazil ....
- [ ] **BY** Belarus ....
- [X] **CA** Canada
- [ ] **CH and LI** Switzerland and Liechtenstein
- [ ] **CN** China ....
- [ ] **CU** Cuba ....
- [X] **CZ** Czech Republic ....
- [ ] **DE** Germany ....
- [ ] **DK** Denmark ....
- [ ] **EE** Estonia ....
- [ ] **ES** Spain ....
- [ ] **FI** Finland ....
- [ ] **GB** United Kingdom
- [ ] **GD** Grenada
- [ ] **GE** Georgia ....
- [ ] **GH** Ghana ....
- [ ] **GM** Gambia
- [ ] **HR** Croatia ....
- [ ] **HU** Hungary ....
- [ ] **ID** Indonesia
- [ ] **IL** Israel ....
- [X] **IN** India ....
- [ ] **IS** Iceland
- [X] **JP** Japan ....
- [ ] **KE** Kenya ....
- [ ] **KG** Kyrgyzstan ....
- [ ] **KP** Democratic People's Republic of Korea ....
- [X] **KR** Republic of Korea ....
- [ ] **KZ** Kazakhstan ....
- [ ] **LC** Saint Lucia
- [ ] **LK** Sri Lanka
- [ ] **LR** Liberia
- [ ] **LS** Lesotho ....
- [ ] **LT** Lithuania
- [ ] **LU** Luxembourg
- [ ] **LV** Latvia ....
- [ ] **MD** Republic of Moldova ....
- [ ] **MG** Madagascar ....
- [ ] **MK** The former Yugoslav Republic of Macedonia ....
- [ ] **MN** Mongolia
- [ ] **MW** Malawi ....
- [ ] **MX** Mexico ....
- [ ] **NO** Norway
- [ ] **NZ** New Zealand ....
- [X] **PL** Poland ....
- [ ] **PT** Portugal ....
- [ ] **RO** Romania
- [X] **RU** Russian Federation ....
- [ ] **SD** Sudan
- [ ] **SE** Sweden
- [ ] **SG** Singapore
- [ ] **SI** Slovenia ....
- [ ] **SK** Slovakia ....
- [ ] **SL** Sierra Leone ....
- [ ] **TJ** Tajikistan ....
- [ ] **TM** Turkmenistan ....
- [ ] **TR** Turkey ....
- [ ] **TT** Trinidad and Tobago ....
- [ ] **UA** Ukraine ....
- [ ] **UG** Uganda ....
- [X] **US** United States of America ....
- [ ] **UZ** Uzbekistan ....
- [ ] **VN** Viet Nam ....
- [ ] **YU** Yugoslavia ....
- [X] **ZA** South Africa ....
- [ ] **ZW** Zimbabwe ....

Check-boxes reserved for designating States which have become party to the PCT after issuance of this sheet:

- [ ] ....
- [ ] ....

Precautionary Designation Statement: In addition to the designations made above, the applicant also makes under Rule 4.9(b) all other designations which would be permitted under the PCT except any designation(s) indicated in the Supplemental Box as being excluded from the scope of this statement. The applicant declares that those additional designations are subject to confirmation and that any designation which is not confirmed before the expiration of 15 months from the priority date is to be regarded as withdrawn by the applicant at the expiration of that time limit. *(Confirmation of a designation consists of the filing of a notice specifying that designation and the payment of the designation and confirmation fees. Confirmation must reach the receiving Office within the 15-month time limit.)*

PCT/SE00/00034

Sheet No. ...4...

12 -01- 2000

Box No. VI PRIORITY CLAIM ☐ Further priority claims are indicated in the Supplemental Box.

Filing date of earlier application (*day/month/year*)	Number of earlier application	Where earlier application is: national application: country	regional application:* regional Office	international application: receiving Office
item (1) 18 Jan -99 18.1 1999	9900113-3	Sweden		
item (2)				
item (3)				

☒ The receiving Office is requested to prepare and transmit to the International Bureau a certified copy of the earlier application(s) *(only if the earlier application was filed with the Office which for the purposes of the present international application is the receiving Office)* identified above as item(s): (1)

* *Where the earlier application is an ARIPO application, it is mandatory to indicate in the Supplemental Box at least one country party to the Paris Convention for the Protection of Industrial Property for which that earlier application was filed (Rule 4.10(b)(ii)). See Supplemental Box.*

Box No. VII INTERNATIONAL SEARCHING AUTHORITY

Choice of International Searching Authority (ISA) *(if two or more International Searching Authorities are competent to carry out the international search, indicate the Authority chosen; the two-letter code may be used)*:

ISA/ SE

RO/SE

Request to use results of earlier search; reference to that search *(if an earlier search has been carried out by or requested from the International Searching Authority)*:

Date *(day/month/year)*	Number	Country *(or regional Office)*
18.01.1999 ~~02.11 1999~~	SE 99/00081	SE

Box No. VIII CHECK LIST; LANGUAGE OF FILING

This international application contains the following **number of sheets**:

request	:	4
description (excluding sequence listing part)	:	20
claims	:	4
abstract	:	1
drawings	:	3
sequence listing part of description	:	
Total number of sheets	:	32

This international application is **accompanied** by the item(s) marked below:

1. ☐ fee calculation sheet
2. ☒ separate signed power of attorney
3. ☐ copy of general power of attorney; reference number, if any:
4. ☐ statement explaining lack of signature
5. ☐ priority document(s) identified in Box No. VI as item(s):
6. ☐ translation of international application into (language):
7. ☐ separate indications concerning deposited microorganism or other biological material
8. ☐ nucleotide and/or amino acid sequence listing in computer readable form
9. ☐ other *(specify)*:

Figure of the drawings which should accompany the abstract: Fig. 3

Language of filing of the international application: Swedish

Box No. IX SIGNATURE OF APPLICANT OR AGENT

Next to each signature, indicate the name of the person signing and the capacity in which the person signs (if such capacity is not obvious from reading the request).

Linköping, January 10, 2000

Jan-Erik Lundmark

For receiving Office use only

1. Date of actual receipt of the purported international application:	12 -01- 2000
3. Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application:	
4. Date of timely receipt of the required corrections under PCT Article 11(2):	
5. International Searching Authority (if two or more are competent):	ISA / SE
6. ☐ Transmittal of search copy delayed until search fee is paid.	

2. Drawings: ☒ received: ☐ not received:

For International Bureau use only

Date of receipt of the record copy by the International Bureau: 15 FEBRUARY 2000 (15.02.00)

1/3

Fig. 1

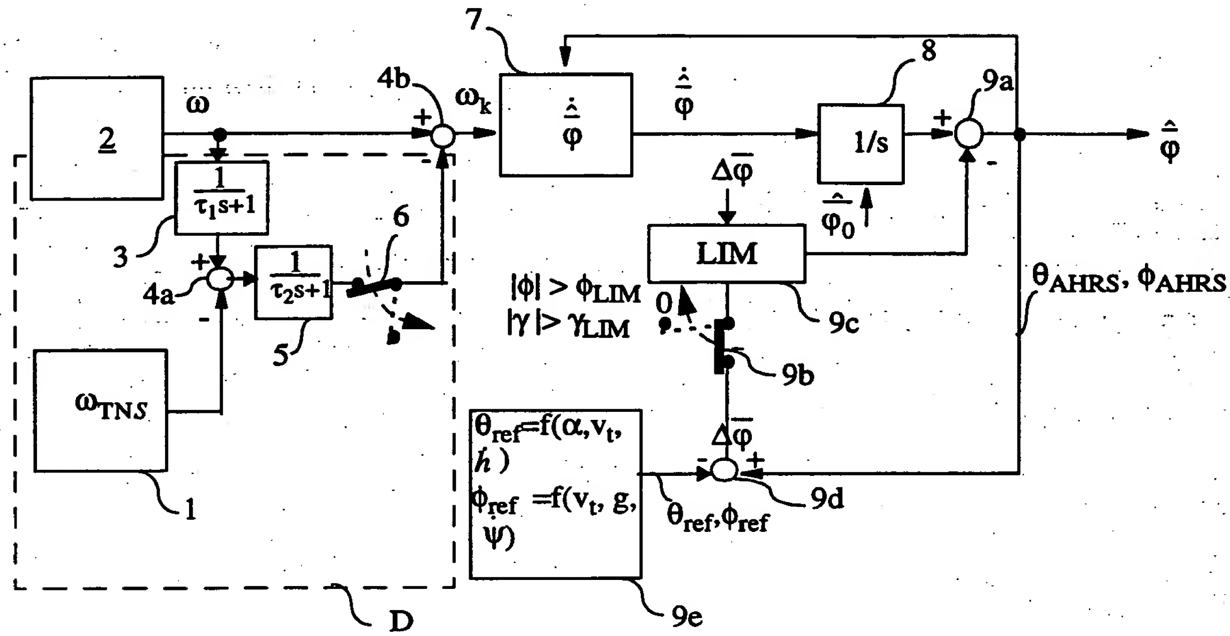
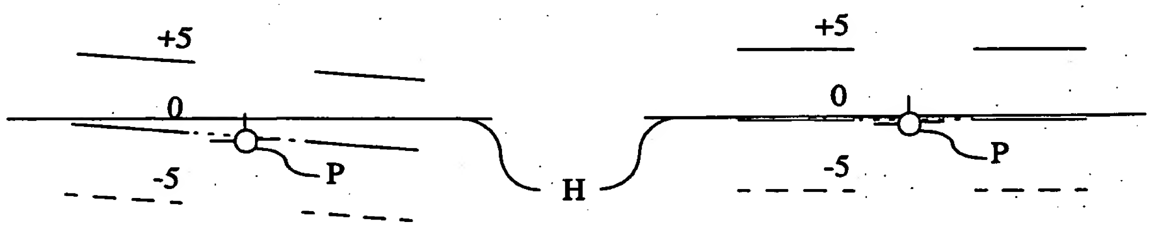

7
8
9a
4b
ω
ω_k
2
1/s
LIM
$\Delta\bar{\varphi}$
3
4a
5
6
$|\phi| > \phi_{LIM}$
$|\gamma| > \gamma_{LIM}$
0
9b
9c
$\theta_{AHRS}, \phi_{AHRS}$
ω_{TNS}
1
$\theta_{ref}=f(\alpha, v_t, h)$
$\phi_{ref} = f(v_t, g, \psi)$
θ_{ref}, ϕ_{ref}
9d
9e
D

Fig. 2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-5
P
H
+5
0
-5
P

2/3

Fig. 3

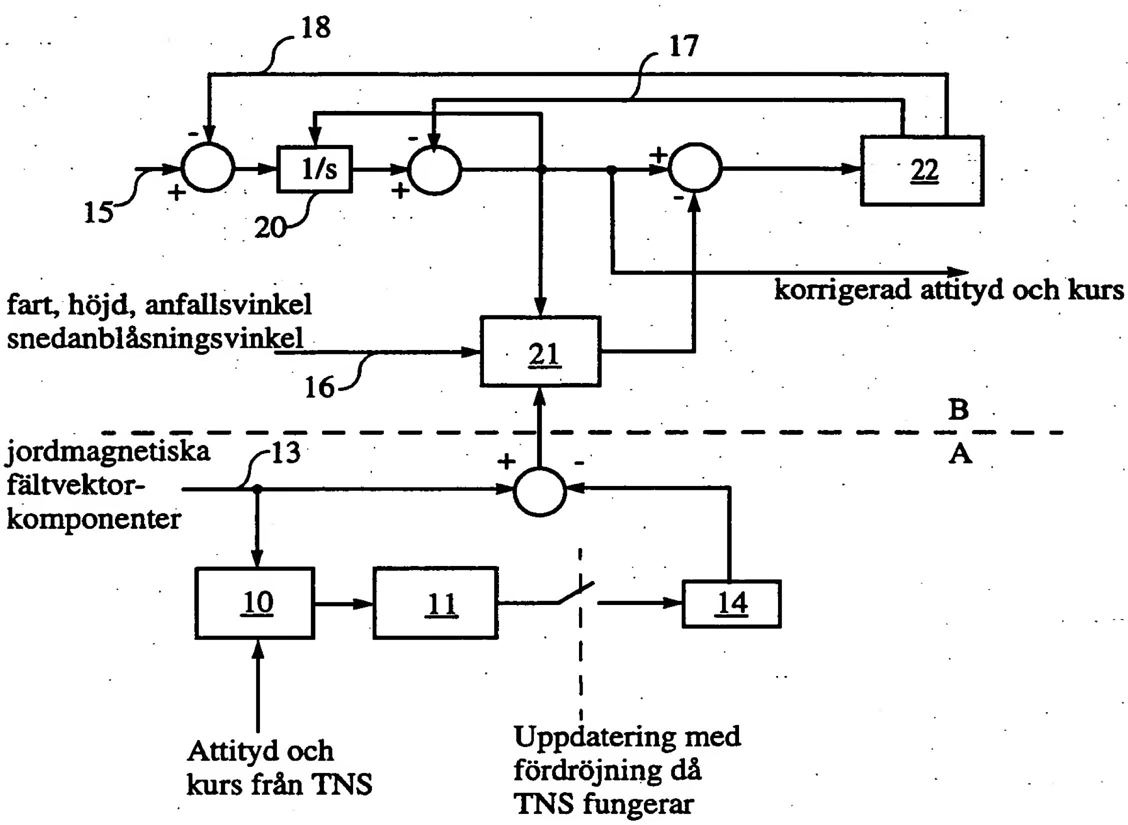
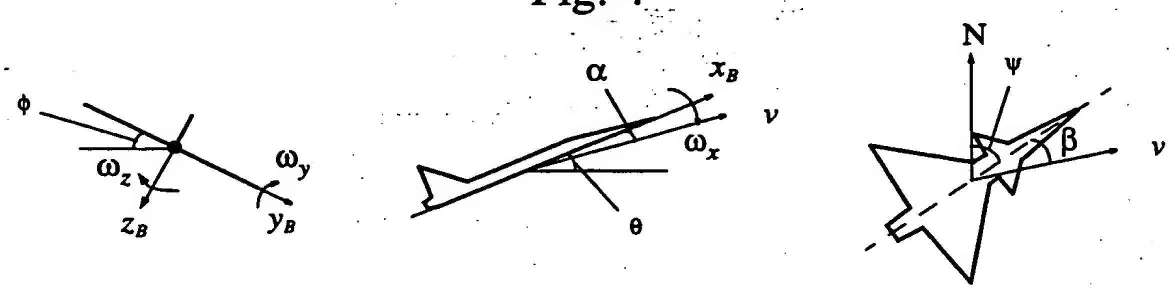
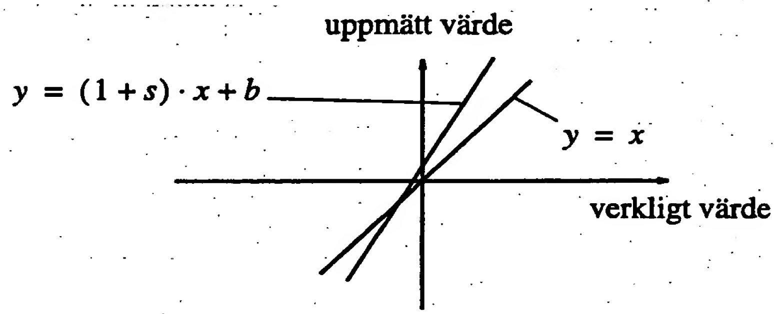

18
17
15
20
1/s
22
fart, höjd, anfallsvinkel
snedanblåsningsvinkel
16
21
korrigerad attityd och kurs
B
A
jordmagnetiska
fältvektor-
komponenter
13
10
11
14
Attityd och
kurs från TNS
Uppdatering med
fördröjning då
TNS fungerar

Fig. 4


N
ψ
β
v
α
x_B
ω_x
θ
ϕ
ω_z
ω_y
z_B
y_B

3/3

Fig. 5



Reservsystem för angivande av kurs och attityd i ett flygplan

TEKNISKT OMRÅDE

Uppfinningen avser en systemfunktion som ger presentation av kurs och flygläge (attityd) på indikatorer i flygplan, t.ex. en siktlinjesindikator (SI), vid fel på viss utrustning för ordinarie flyglägespresentation. Systemfunktionen, som på engelska benämns Attitude and Heading Reference System och förkortas AHRS efter initialerna, kompletterar flygplanets ordinarie presentation för kurs och flygläge. Denna presentation ska hjälpa piloten att ta sig ur svåra flyglägen och sedan underlätta hemflygning/landning.

TEKNIKENS STÅNDPUNKT

För att inte tappa attityd- och kurspresentation i ett flygplan vid bortfall av ett ordinarie använt tröghetsnavigeringssystem (TNS) krävs ett reservsystem. Vid god sikt kan en pilot flyga genom att använda horisonten som attitydreferens, dock med stor osäkerhet om kursen. I dåligt väder, i moln och nattetid när horisonten ej är synlig kan piloten snabbt bli desorienterad och därvid försätta flygplanet och sig själv i farliga situationer.

AHRS-system beräknar, oberoende av ordinarie system, attitydvinklar (tipp och roll) och flygriktning (kursen). Ett sådant system presenterar kontinuerligt läget för piloten på en indikator i kabin. Behovet av ett reservsystem för attityd kan vara så stort att flygplan utan ett fungerande sådant inte tillåts att flyga.

Reservsystem i form av en AHRS apparat finns tillgänglig idag. En sådan innehåller bl a gyron som mäter lägesförändringar i tipp-, roll- och girled för flygplanet. Den innehåller vidare accelerometrar och magnetiska sensorer. Accelerometrarna används för att etablera ett horisontalplan. Magnetsensorerna används för att åstadkomma en magnetisk nordände. Denna typ av AHRS-system i apparatform är dyrbara enheter och medför installation av vikt- och utrymmeskrävande utrustning i flygplanet. För att råda bot på detta föreslås i denna beskrivning en syntetisk AHRS som använder i flygplanet befintliga givare, vilka normalt inte

är avsedda för AHRS-beräkningar och därmed delvis med väsentligt sämre prestanda, istället för givare av den typ som ingår i en AHRS-apparat.

Vinklarna beräknas med hjälp av i flygplanet befintliga givare. Syftet är att använda befintliga vinkelhastighetsgyrosignaler och stötta dessa med beräkningar utgående från andra tillgängliga primärdata i flygplanet. Vinkelhastighetsgyron används normalt i styrsystem och har i allmänhet väsentligt större drift än gyron för navigering.

BESKRIVNING AV UPPFINNINGEN

Enligt en aspekt av uppfinningen tillhandahålls en metod för att syntetiskt beräkna reservattityd och reservkurs medelst i ett flygplan befintliga data såsom specificerat i patentkraven.

Olika utförandeformer har utvecklats. Vid ett utförande finns flygplanets kurs tillgänglig och vid ett annat utförande beräknas kursen utifrån en magnetisk kursgivare. När kursen finns tillgänglig kan beräkningarna reduceras väsentligt.

Då kursen är tillgänglig (reservkurs) sker beräkningen av attityd genom sammanvägning av signalerna från vinkelhastighetsgyrona i flygplanets styrsystem, information från luftdata (höjd, fart, anfallsvinkel) samt information om kurs (reservkurs).

Då kursen inte är tillgänglig sker beräkningen av attityd och kurs enligt ett utförande med hjälp av kalmanfilter genom sammanvägning av signalerna från vinkelhastighetsgyrona i flygplanets styrsystem, information från luftdata (höjd, fart, anfallsvinkel och snedanblåsningsvinkel) samt information från en i flygplanet befintlig magnetkursdetektor.

En fördel med en syntetisk AHRS enligt uppfinningsaspekten är att den ställer sig väsentligt billigare än konventionella på egna givare baserade AHRS-system om befintliga givare i flygplanet kan användas. Då frigörs utrymme och vikt i flygplanet.

FIGURBESKRIVNING

Figur 1 visar en schematisk bild över en AHRS-funktion, där kursen är tillgänglig.

Figur 2 visar principen för invridning av läget för flygplanet i en siktlinjesindikator, till vänster utan invridning och till höger med invridning.

Figur 3 visar blockschemat för ett reservsystem för både attityd och kurs.

Figur 4 visar i tre bilder flygplanets attityd och kurs samt axlarna i det skrovfasta koodinatsystemet (body frame) samt anfallsvinkel och snedanblåsningsvinkel.

Figur 5 visar hur nollfel och skalfaktorfel slår igenom på uppmätt värde.

BESKRIVNING AV UTFÖRINGSFORMER

Ett antal utföranden beskrivs i det följande med stöd av figurerna. Enligt uppfinningen tillhandahålls metoder för att syntetiskt beräkna attityd och kurs medelst i flygplanet befintliga data såsom specificerat i patentkraven.

Vid ett enklare utförande finns flygplanets kurs tillgänglig. Vid ett annat utförande beräknas kursen, i detta fall utifrån en magnetisk kursgivare.

AHRS-beräkning när kursen är känd

För att bestämma flygplanets orientering relativt referenskoordinatsystemet N (navigation frame) används signalerna från de tre skrovfast monterade vinkelhastighetsgyrona 2. Vinkelhastighetsgyrona 2 mäter vinkelhastigheter omkring de tre kroppsfasta koordinataxlarna (x, y, z). Vinkelhastigheterna brukar normalt ha beteckningen ω_x eller p (rotation kring x-axeln), ω_y eller q (rotation kring y-axeln) och ω_z eller r (rotation kring z-axeln). Orienteringen mellan det skrovfasta koordinatsystemet B (body) och N-systemet ges

av eulervinklarna θ, ϕ och ψ. Eftersom kursen är känd är dock bara θ och ϕ av intresse. Med antagandet att N-systemet är ett inertialsystem och orienterat så att dess z-axel är parallell med jordens g-vektor kan man visa att

$$\begin{bmatrix}\dot{\theta}\\ \dot{\phi}\end{bmatrix} = \begin{bmatrix}\omega_y\cos\phi - \omega_z\sin\phi\\ \omega_x + \tan\theta(\omega_y\sin\phi + \omega_z\cos\phi)\end{bmatrix} \quad (1)$$

Om gyrona 2 vore ideala, begynnelsevärdena ϕ_0 och θ_0 felfria och om integrationsmetoden som används vore exakt kan attitydvinklar erhållas genom att ekv (1) löses. I praktiken är dock inga av dessa förutsättningar uppfyllda, utan sensorfel m.m. gör att lösningen divergerar och relativt snart blir oanvändbar.

Sensorfel i form av bl a nollfel, skalfaktorfel, snedmontering och accelerationsinducerade drifter utgör de dominerande felkällorna. I planflykt är nollfelet den felkälla som dominerar feltillväxten.

På grund av sensorofullkomligheter och osäkerhet i begynnelsevärden ger ekvation (1) en skattning av roll- och tippvinkelderivator enligt

$$\dot{\hat{\bar{\varphi}}} = \begin{bmatrix}\dot{\hat{\theta}}\\ \dot{\hat{\phi}}\end{bmatrix} = \begin{bmatrix}\omega_y\cos\hat{\phi} - \omega_z\sin\hat{\phi}\\ \omega_x + \tan\hat{\theta}(\omega_y\sin\hat{\phi} + \omega_z\cos\hat{\phi})\end{bmatrix} \quad (2)$$

Skillnaden mellan förväntade $\hat{\bar{\varphi}}_{AHRS}$ (av AHRS-funktionen beräknade) och "verkliga" $\bar{\varphi}_{ref}$ (av luftdata, primärdata beräknade) attitydvinklar utgör en skattning av attitydfelet

$$\Delta\bar{\varphi} = \hat{\bar{\varphi}}_{AHRS} - \bar{\varphi}_{ref} \quad (3)$$

Se nedan avseende användning av $\Delta\bar{\varphi}$.

Attitydvinklarna ges slutligen som

$$\hat{\varphi}_{AHRS} = \int_t \left(\hat{\dot{\varphi}}\right) dt + \hat{\varphi}_0 - lim(\Delta\bar{\varphi}) \qquad (4)$$

där $\hat{\varphi}_0$ utgör skattade begynnelsevärden.

Beräkning av $\bar{\varphi}_{ref}$

Vid beräkning av θ_{ref} används formeln $\theta_{ref} = \arcsin(\dot{h}/v_t) + (\alpha * \cos\phi)$. $\dot{h}$ är en högpassfiltrerad höjdsignal. v_t är true airspeed.

Vid beräkning av ϕ_{ref} används formeln $\phi_{ref} = \arctan(v_t * (\dot{\psi})/g)$.

$\dot{\psi}$ är en högpassfiltrerad kurs(reservkurs)-signal.

Nollkorrigering av vinkelhastighetsgyron

Nollfelen i vinkelhastighetsgyrona 2 är starkt temperaturberoende. Det kan ta 20-30 minuter för gyrona att uppnå driftstemperatur. Detta medför att ett TNS-fel kort efter start skulle kunna ge stora nollfel vid fortsatt flygning. Det tar dock en viss tid från det att gyrona 2 erhåller spänning till dess att flygplanet lättar, vilket innebär att en del av temperaturinsvängningen är genomförd när ett flygpass inleds. Dessutom förutsätts att landning kan ske inom kort tid vid TNS-fel under start. För att minimera nollfel från vinkelhastighetsgyrona 2 utförs en nollkorrigering av vinkelhastighetsgyrona med programvara. Detta går ut på att ω (p, q och r) - signalerna från vinkelhastighetsgyrona 2 jämförs med motsvarande signaler från TNS, se ekv (5), genom en skillnadsbildning i 4a. Skillnaden lågpassfiltreras i ett filter 5 och läggs till vinkelhastighetsgyrosignalerna i en skillnadsbildare 4b, varvid signalen ω_k som betecknar de nollfelskorrigerade gyrosignalerna erhålls och används istället för ω i AHRS-beräkningarna. Detta sker kontinuerligt så länge TNS fungerar. Vid ett TNS-fel utnyttjas de sist utförda nollkorrigeringarna för resten av flygningen.

$$\omega_{TNS} = \begin{bmatrix} p_{TNS} \\ q_{TNS} \\ r_{TNS} \end{bmatrix} = \begin{bmatrix} \dot{\phi}_{TNS} - \dot{\psi}_{TNS}\sin\theta_{TNS} \\ \dot{\theta}_{TNS}\cos\phi_{TNS} + \dot{\psi}_{TNS}\cos\theta_{TNS}\sin\phi_{TNS} \\ -\dot{\theta}_{TNS}\sin\phi_{TNS} + \dot{\psi}_{TNS}\cos\theta_{TNS}\cos\phi_{TNS} \end{bmatrix} \quad (5)$$

Ett blockschema över realiseringen av AHRS-funktionen med nollkorrigering av vinkelhastighetsgyrona återges i figur 1. Figuren ger en schematisk bild av AHRS-funktionen. Nollkorrigeringen av vinkelhastighetsgyrona utförs av enheterna innanför det streckade området D.

ψ_{TNS}, θ_{TNS} och ϕ_{TNS} högpassfiltreras för att erhålla $\dot{\psi}_{TNS}$, $\dot{\theta}_{TNS}$ och $\dot{\phi}_{TNS}$. Dessa används i ekv (5), vilken ger ω_{TNS} (p_{TNS}, q_{TNS}, r_{TNS}) i ett första block 1. ω (p, q, r) som erhålls som signaler från gyrona betecknade med 2 i ett andra block lågpassfiltreras i ett lågpassfilter 3 innan skillnadsbildningen sker i 4a.

Skillnadssignalen mellan ω_{TNS} (p_{TNS}, q_{TNS}, r_{TNS})-signalerna och ω (p, q, r)-signalerna lågpassfiltreras med lång tidskonstant i ett lågpassfilter 5, dvs. medelvärdesbildas under lång tid. Filtret 5 initialsätts vid startrotation med en kortare tidskonstant. Efter ett kraftavbrott initialsätts filtret 5 momentant.

I blocket 7 beräknas $\dot{\hat{\bar{\varphi}}}$, varefter integrationen enligt ekvation (4) utförs i en integrator 8, till vilken begynnelsevillkoren $\bar{\varphi}_0$ förs. I en skillnadsbildare 9a tillförs signalen $\Delta\bar{\varphi}$ som dock kopplas bort medelst en brytare 9b under vissa omkopplingsvillkor, som t ex när $|\gamma| > \gamma_{LIM}$ samt $|\phi| > \phi_{LIM}$. $\Delta\bar{\varphi}$-signalen passerar en begränsare 9c. Storleken på utsignalen från begränsaren 9c är beroende av storleken på $\Delta\bar{\varphi}$-signalen (dvs insignalen till begränsare 9c). $\Delta\bar{\varphi}$-signalen bildas enligt ekv (3) i en skillnadsbildare 9d till villken förs beräknade $\hat{\bar{\varphi}}_{AHRS}$ -attitydvinklar och "verkliga" $\bar{\varphi}_{ref}$ -attitydvinklar från givare (primärdata) betecknade med 9e.

De framräknade vinklarna från AHRS innehåller trots kompenseringar små nollfel. Då utsignalerna används för presentation i SI korrigeras detta genom användning av $\Delta\phi$ i rolled och $\Delta\theta$ i tippled för att vrida in SI bilden tills ett stabilt läge erhållits. Se figur 2, där linjen H

symboliserar verklig horisont och där ett flygplan representeras av P. Observera att denna invridning av SI-bilden endast sker då man ligger innanför ovan redovisade gränser.

AHRS-beräkning när även kursen ska beräknas

Figur 3 åskådliggör schematiskt de moduler som utgör byggblock för en andra variant av en syntetisk AHRS och hur dessa moduler är sammanlänkade för att skapa en reservattityd och en reservkurs.

Figur 3 åskådliggör principen för reservsystemet enligt uppfinningsaspekten. Systemet består av två delsystem A och B; det första delsystemet A utför skattning av eventuella fel i uppmätt jordmagnetiskt fält och det andra delsystemtet B utför beräkning av reservattityd och kurs. Totalt leder detta till fem byggblock, där en första mätrutin 10 och ett första kalmanfilter 11 utgör byggblocken i det första delsystemet A och vidare där integrationsrutinen (1/s) 20, mätrutin 21 och ett andra kalmanfilter 22 utgör byggblocken i det andra delsystemet B. Med mätrutin 10 transformeras uppmätta fältvektorkomponenter i det skrovfasta koordinatsystemet, kallat body frame, till ett nordligt, östligt och vertikalt orienterat koordinatsystem, kallat navigation frame. Transformationen sker med hjälp av attityd och kurs från flygplanets tröghetsnavigeringssystem, TNS, via ledning 12. De jordmagnetiska fältvektorkomponenterna, hämtas från en i flygplanet befintlig magnetkursgivare och inkommer via ledning 13. I det första kalmanfiltret 11 skattas sedan felen i fältvektorkomponenterna utifrån information om hur komponenterna nominellt ska vara beskaffade, varefter de skattade värdena lagras i ett minne 14.

Delsystem A (mätrutin 10 och kalmanfilter 11) används bara då TNS fungerar felfritt. Vid eventuellt bortfall av TNS används senast möjliga skattning av felen i fältvektorkomponenterna, dvs det som finns undanlagrat i minnet 14. Eftersom det i många fall kan vara svårt att avgöra om TNS fungerar som det ska, bör inte den absolut senaste skattningen utnyttjas. För att lösa detta är de skattningar av fel i uppmätt jordmagnetiskt fält som används minst ett flygpass gammalt, dvs de skattningar som finns lagrade i minnet är från föregående flygpass eller tidigare.

Integrationsrutinen 20 får information om vinkelhastigheter, i det här fallet för de tre koordinataxlarna x, y och z i body frame. Dessa brukar normalt ha beteckningen ω_x eller p (rotation kring x-axeln), ω_y eller q (rotation kring y-axeln) och ω_z eller r (rotation kring z-axeln). Informationen hämtas från styrsystemets vinkelhastighetsgyron och matas via ledningen 15 till rutinen 20 som integrerar fram attityd och kurs via en transformationsmatris.

Den andra mätrutinen 21 består av en utvecklad variant av den första mätrutinen 11 och använder de från den första mätrutinen 11 erhållna devierade fältvektorkomponenterna. Dessutom beräknas en roll- och tippvinkel med hjälp av data från befintliga luftdata och befintliga anblåsningsgivare, vilka data inkommer via ledning 16 till mätrutinen 21. Medelst det andra kalmanfiltret 22 skattas sedan i första hand de attityd- och kursfel som uppstår vid integrationen av styrsystemets vinkelhastighetsgyrosignaler. I andra hand används kalmanfilter 22 för att skatta nollfelen i vinkelhastighetsgyrosignalerna, dvs nollfelen i p, q, och r.

Den första mätrutinen 10

Det jordmagnetiska fältet kan beräknas teoretiskt över hela världen. För att göra detta används exempelvis IGRF (International Geomagnetic Reference Field).
Fältvektorn i body frame betecknas här med B_B och fältvektorn i navigation frame med B_N. Vidare betecknas de tre komponenterna av fältvektorn enligt

$$B = [B_x, B_y, B_z]^T \quad (6)$$

Med hjälp av transformationsmatrisen C_B^N, som transformerar en vektor från body frame till navigation frame, har vi att

$$B_N = C_B^N \cdot B_B , \quad (7)$$

där C_B^N har utseendet

$$C_B^N = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \quad (8)$$

Transformationsmatrisen C_B^N beräknas med hjälp av attityd och kurs, θ, ϕ, ψ, från TNS. Skillnaden mellan uppmätt och enligt modellen beräknad fältvektor blir

$$B_{N,\,\mathrm{Uppmätt}} - B_{N,\,\mathrm{Beräknad}} = C_B^N \cdot \delta B_B\,, \tag{9}$$

där δ betecknar skillnaden i uppmätt storhet och beräknad.

Vänsterledet i ekv (9) blir utsignal från den första mätrutinen 10 och därmed insignal till kalmanfilter 11. Vidare utnyttjas högerledet i ekv (9) i kalmanfiltret 11, vilket framgår av beskrivningen av funktionen för det första kalmanfiltret 11 nedan.

Det första kalmanfiltret 11

Givet tillståndsmodellen

$$\begin{aligned} x_{k+1} &= F_k x_k + w_k \\ z_k &= H_k x_k + e_k, \end{aligned} \tag{10}$$

så arbetar ett kalmanfilter enligt:

Tidsuppdatering

$$\begin{aligned} x^-_{k+1} &= F_k x^+_k \\ P^-_{k+1} &= F_k P^+_k F^T_k + Q_k, \end{aligned} \tag{11}$$

där P^-_{k+1} är skattad osäkerhet för tillstånden efter tidsuppdateringen.

Mätuppdatering

$$\begin{aligned} K_{k+1} &= P^-_{k+1} H^T_{k+1} [H_{k+1} P^-_{k+1} H^T_{k+1} + R_{k+1}]^{-1} \\ x^+_{k+1} &= x^-_{k+1} + K_{k+1}[z_{k+1} - H_{k+1} x^-_{k+1}] \\ P^+_{k+1} &= P^-_{k+1} - K_{k+1} H_{k+1} P^-_{k+1}, \end{aligned} \tag{12}$$

där P^+_{k+1} är skattad osäkerhet för tillstånden efter mätuppdateringen.

Felen i fältvektorkomponenterna modelleras enligt

$$\begin{bmatrix} \delta B_x \\ \delta B_y \\ \delta B_z \end{bmatrix} = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} + \begin{bmatrix} s_x & k_{xy} & k_{xz} \\ k_{yx} & s_y & k_{yz} \\ k_{zx} & k_{zy} & s_z \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix}, \tag{13}$$

där b är nollfel, s är skalfaktorfel och k är en korskoppling från en komponent till en annan (tex så innebär index xy hur y-komponenten påverkar x-komponenten). Dessa 12 fel får representera tillstånden i det första kalmanfiltret 11 enligt

$$x_k = \begin{bmatrix} b_x \ b_y \ b_z \ s_x \ s_y \ s_z \ k_{xy} \ k_{xz} \ k_{yz} \ k_{yx} \ k_{zx} \ k_{zy} \end{bmatrix}^T \tag{14}$$

och tillståndsekvationerna får var och en utseendet

$$x_{k+1} = x_k + w_k , \tag{15}$$

där index k betecknar den tidsdiskreta uppräkningen i tid.

I ekv (15) är w_k ett svagt tidsdiskret processbrus för att modellera en viss drift i felen. Ekv (15) medför att prediktionsmatrisen blir enhetsmatrisen och kovariansmatrisen för processbruset blir enhetsmatrisen multiplicerat med σ_w^2, där σ_w är satt till typiskt en hundratusendel (dimensionslöst eftersom fältvektorkomponenterna normeras till beloppet 1 innan de utnyttjas).

När det gäller mätuppdateringen av kalmanfilter 11 utnyttjas ekv (9) och mätmatrisen får utseendet

$$H_k = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{11}B_x & c_{12}B_y & c_{13}B_z & c_{11}B_y & c_{11}B_z & c_{12}B_z & c_{12}B_x & c_{13}B_x & c_{13}B_y \\ c_{21} & c_{22} & c_{23} & c_{21}B_x & c_{22}B_y & c_{23}B_z & c_{21}B_y & c_{21}B_z & c_{22}B_z & c_{22}B_x & c_{23}B_x & c_{23}B_y \\ c_{31} & c_{32} & c_{33} & c_{31}B_x & c_{32}B_y & c_{33}B_z & c_{31}B_y & c_{31}B_z & c_{32}B_z & c_{32}B_x & c_{33}B_x & c_{33}B_y \end{bmatrix} \tag{16}$$

På grund av omodellerade störningar kommer uppmätt jordmagnetisk fältvektor att deviera från modellen, både till riktning och belopp. Den enklaste varianten är att modellera dessa störningar som ett konstant vitt mätbrus med hjälp av mätbruskovariansmatrisen R_k. Standardavvikelsen för mätbruset för de tre fältvektorkomponentmätningarna är vardera satta till typiskt en tiondel (dimensionslöst eftersom fältvektorkomponenterna normeras till beloppet 1 innan de utnyttjas).

För att undvika genomslag av dåliga mätningar utnyttjas ett Chi2-test. Dessutom utnyttjas inte mätningarna av fältvektorkomponenterna om vinkelhastigheterna är för höga. Detta har sin grund i att diverse tidsfördröjningar slår igenom vid höga vinkelhastigheter.

Integrationsrutinen 20

Man kan visa att tidsderivatan av transformationsmatrisen C_B^N blir

$$\dot{C}_B^N = C_B^N \cdot W_{IB} - W_{IN} \cdot C_B^N . \qquad (17)$$

I ekv (17) är W_{IB} och W_{IN} B:s (Body frame) rotation relativt I (Inertial frame) respektive N:s (Navigation frame) relativt I, båda skrivna i matrisform.

Eftersom det här handlar om reservattityd och reservkurs, där kraven på fel i attityd är av storleksordningen 2 grader, samtidigt som elementen i W_{IN} är av storleksordningen 0.01 grader, försummas W_{IN}. Uttrycket i (17) blir då

$$\dot{C}_B^N = C_B^N \cdot W_{IB} , \qquad (18)$$

där W_{IB} är vinkelhastighetsgyrosignalerna från styrsystemets vinkelhastighetsgyron.

I princip innebär ekv (18) att man har nio differentialekvationer. På grund av ortogonalitet behöver endast sex av dessa integreras och de övriga tre kan beräknas med hjälp av kryssprodukten.

Den andra mätrutinen 21

Den andra mätrutinen 21 består av en utvecklad variant av den första mätrutinen 11, där utvidgningen består av en beräkning av roll- och tippvinkel med hjälp av data från luftdata (höjd och fart) och anblåsningsgivarna (anfallsvinkel och snedanblåsningsvinkel).

I den första mätrutinen 21 antas att endast fältvektorkomponenterna är felaktiga och att attityd och kurs är korrekta. Detta antagande är rimligt på grund av att en resolvering av fältvektorkomponenterna sker med hjälp av attityd och kurs från TNS. I den andra mätrutinen 21 är detta inte uppfyllt, utan hänsyn måste även tas till fel i attityd och kurs. Fältvektorn som används i den andra mätrutinen 21 är kompenserad för fel skattade i delsystem A.

Fel i både fältvektorn och transformationsmatrisen ger att

$$B_{N,\,\mathrm{Uppmätt}} = \hat{C}_B^N \cdot B_{B,\,\mathrm{Uppmätt}} , \qquad (19)$$

där $\hat{C}_B^N$ står för beräknad transformationsmatris och betyder att

$$\hat{C}_B^N = C_B^N + \delta C_B^N. \tag{20}$$

Utnyttjar vi (20), bildar skillnaden mellan uppmätt och beräknad fältvektor och försummar produkter av fel fås att

$$B_{N,\,\text{Uppmätt}} - B_{N,\,\text{Beräknad}} \approx \delta C_B^N \cdot B_{N,\,\text{Uppmätt}} + \hat{C}_B^N \cdot \delta B_B\,. \tag{21}$$

I den andra mätrutinen 21 sker även beräkning av roll- och tippvinkel med hjälp av höjd, fart, anfallsvinkel och snedanblåsningsvinkel. Tippvinkeln kan beräknas enligt

$$\theta_{\text{ref}} = \operatorname{asin}\left(\frac{\dot{h}}{v}\right) + \cos(\phi)\alpha + \sin(\phi)\beta \tag{22}$$

För att kunna beräkna tippvinkeln enligt uttrycket i ekv (22) krävs en höjdderivata. Denna höjdderivata är inte direkt tillgänglig, utan den får beräknas utifrån befintlig höjd som erhålls från luftdata. Beräkningen görs enligt

$$\dot{h} = \dot{h}(n) = \frac{1}{\tau}\left(\left(\tau - \frac{1}{f_s}\right) \cdot \dot{h}(n-1) + h(n) - h(n-1)\right), \tag{23}$$

dvs en högpassfiltrering av höjden. Beteckningarna τ och f_s i ekv (23) representerar filtreringens tidskonstant respektive sampelfrekvens. Farten v som används i ekv (22) är approximativt v_t (sann fart relativt luften). Med approximativt menas att vid beräkningen av v_t används inte uppmätt temperatur, vilket är det normala, utan här utnyttjas en sk standardtemperaturfördelning.

Vidare så kan rollvinkeln beräknas enligt

$$\phi_{\text{ref}} = \operatorname{atan}\frac{v\dot{\psi}}{g}. \tag{24}$$

Uttrycket i ekv (24) gäller endast för små roll- och tippvinklar, små vinkelhastigheter och dessutom att anfalls- och snedanblåsningsvinklarna är små.

Ovanstående två uttryck beräknas och jämförs med den attityd som beräknas via integrationsrutinen genom att skillnaden bildas enligt

$$\phi - \phi_{ref} = \operatorname{atan}\frac{c_{32}}{c_{33}} - \operatorname{atan}\frac{v(c_{33}\cdot\omega_z + c_{32}\cdot\omega_y)}{g(c_{11}^2 + c_{21}^2)}$$

$$\theta - \theta_{ref} = \operatorname{atan}\frac{-c_{31}}{\sqrt{1-c_{31}^2}} - \left(\operatorname{asin}\left(\frac{\dot{h}}{v}\right) + \cos\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\alpha + \sin\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\beta\right), \tag{25}$$

där

$$\phi = \operatorname{atan}\frac{c_{32}}{c_{33}}$$

$$\theta = \operatorname{atan}\frac{-c_{31}}{\sqrt{1-c_{31}^2}} \tag{26}$$

$$\dot{\psi} = \frac{c_{33}\cdot\omega_z + c_{32}\cdot\omega_y}{c_{11}^2 + c_{21}^2}.$$

Det andra kalmanfiltret 22

Det andra kalmanfiltret 22 kan sägas vara hjärtat i systemet. Här skattas de attityd- och kursfel som uppstår vid integrationen av vinkelhastighetsgyrosignalerna från styrsystemet. Skattning sker även av nollfelen i vinkelhastighetsgyrosignalerna. Vidare skattas eventuella återstående fel i fältvektorkomponenterna, dvs de fel som det första kalmanfiltret 11 inte kommer åt. Allt som allt innebär detta nio tillstånd; tre för attityd- och kursfel, tre för nollfelen i vinkelhastighetsgyrosignalerna och tre för återstående fel i fältvektorkomponenterna (tre nollfel).

Attityd- och kursfel representeras med en vridning av det skrovfasta systemet (body frame) från beräknat till sant koordinatsystem. Felet i $\hat{C}_B^N$ kan skrivas som

$$\delta C_B^N = \hat{C}_B^N - C_B^N = C_B^N \cdot C_{\hat{B}}^B - C_B^N = C_B^N \cdot (C_{\hat{B}}^B - I). \tag{27}$$

Man kan övertyga sig om att

$$C_{\hat{B}}^B = \begin{bmatrix} 1 & -\gamma_z & \gamma_y \\ \gamma_z & 1 & -\gamma_x \\ -\gamma_y & \gamma_x & 1 \end{bmatrix} = \Gamma + I, \tag{28}$$

där Γ är matrisformen av $\gamma = [\gamma_x, \gamma_y, \gamma_z]^T$ och I är enhetsmatrisen (T betecknar transponat). Elementen i vektorn γ beskriver en liten rotation kring respektive axel mellan verkligt (sant) och beräknat skrovfast system (body frame). Motsvarande differentialekvationer för elementen i γ kan härledas till

$$\dot{\gamma} = \delta\omega, \tag{29}$$

där $\delta\omega$ är felen i vinkelhastigheterna från vinkelhastighetsgyrona.

Felen i vinkelhastigheterna, modelleras som tre 1:a ordningens Markovprocesser enligt

$$\delta\dot{\omega} = -\frac{1}{\tau_\omega}\delta\omega + u_\omega \tag{30}$$

där tidskonstanten τ_ω är satt till typiskt ett antal timmar och de tre u_ω till typiskt mindre än en grad/sek.

På ett liknande sätt är återstående fel i fältvektorkomponenterna modellerade (nollfelen), dvs

$$\dot{b} = -\frac{1}{\tau_b}b + u_b \tag{31}$$

där τ_b är satt till typiskt ett antal timmar, och u_b och är satt till typiskt ett par hundradelar (dimensionslöst eftersom fältvektorkomponenterna normeras till beloppet 1 innan de utnyttjas).

Detta ger en tillståndsvektor enligt

$$x_k = \left[\gamma_x\ \gamma_y\ \gamma_z\ \delta\omega_x\ \delta\omega_y\ \delta\omega_z\ b_x\ b_y\ b_z\right]^T \tag{32}$$

och en prediktionsmatris enligt

$$F_k = I + \int_t^{t+\Delta T} A(\tau)d\tau, \tag{33}$$

där $A(\tau)$ är den matris som beskriver de tidskontinuerliga tillståndsekvationerna enligt ovan. Kovariansmatrisen för processbruset Q_k är satt till en diagonalmatris. Som diagonalelement utnyttjas bla u_ω och u_b beskrivna ovan. När det gäller diagonalelementen kopplade till tillstånden för attityd- och kursfel (de tre första) tas effekterna av skalfaktorfelen i

vinkelhastighetsgyrosignalerna med. Dessa skalfaktorfel är normalt i storleksordningen 2% och kan ge stora fel i framintegrerad attityd och kurs vid höga vinkelhastigheter.

Mätningarna är fem till antalet; tre devierade fältvektorkomponenter och roll- och tippvinkel beräknade utifrån luftdata. Dessa mätningar erhålls genom att relationerna (21) och (25) utnyttjas.

När det gäller mätmatrisen H_k, utnyttjas relation (21) för att fylla de tre översta raderna. Detta ger att de tre översta raderna i mätmatrisen får utseendet

$$H_{k,1-3} = \begin{bmatrix} c_{13}B_y - c_{12}B_z & c_{11}B_z - c_{13}B_x & c_{12}B_x - c_{11}B_y & 0 & 0 & 0 & c_{11} & c_{12} & c_{13} \\ c_{23}B_y - c_{22}B_z & c_{21}B_z - c_{23}B_x & c_{22}B_x - c_{21}B_y & 0 & 0 & 0 & c_{21} & c_{22} & c_{23} \\ c_{33}B_y - c_{32}B_z & c_{31}B_z - c_{33}B_x & c_{32}B_x - c_{31}B_y & 0 & 0 & 0 & c_{31} & c_{32} & c_{33} \end{bmatrix} \quad (34)$$

Till de två sista raderna i H_k utnyttjas ekv (25) genom att de båda högerleden differentieras med avseende på alla tillstånd i det andra kalmanfiltret 22. Detta ger att de båda sista raderna får elementen (indexet betecknar rad och kolumn i nämnd ordning)

$$\begin{aligned}
h_{41} &= 1 - \frac{vg(c_{33}\omega_y - c_{32}\omega_z)(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33}\cdot\omega_z + c_{32}\cdot\omega_y)^2} \\
h_{42} &= \frac{2vg(-c_{11}c_{13} - c_{21}c_{23})(c_{33}\omega_z + c_{32}\omega_y) - vg\omega_z c_{31}(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33}\cdot\omega_z + c_{32}\cdot\omega_y)^2} - \frac{c_{31}c_{32}}{c_{32}^2 + c_{33}^2} \\
h_{43} &= \frac{2vg(c_{11}c_{12} + c_{21}c_{22})(c_{33}\omega_z + c_{32}\omega_y) + vg\omega_y c_{31}(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33}\cdot\omega_z + c_{32}\cdot\omega_y)^2} - \frac{c_{31}c_{33}}{c_{32}^2 + c_{33}^2} \qquad (35) \\
h_{45} &= -\frac{vgc_{32}(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33}\cdot\omega_z + c_{32}\cdot\omega_y)^2} \\
h_{46} &= -\frac{vgc_{33}(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33}\cdot\omega_z + c_{32}\cdot\omega_y)^2}
\end{aligned}$$

och

$$h_{51} = \sin\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\alpha - \cos\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\beta$$

$$h_{52} = \frac{c_{33}}{\sqrt{1-c_{31}^2}} + \frac{c_{32}c_{31}}{c_{32}^2+c_{33}^2}\left(-\sin\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\alpha + \cos\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\beta\right) \quad (36)$$

$$h_{53} = -\frac{c_{32}}{\sqrt{1-c_{31}^2}} - \frac{c_{33}c_{31}}{c_{32}^2+c_{33}^2}\left(\sin\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\alpha - \cos\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\beta\right).$$

Övriga element i fjärde och femte raden är noll.

Kovariansmatrisen för mätbruset R_k väljs enklast till en diagonalmatris. De fyra första mätbruselementen har en standardavvikelse som är satta till typiskt en tiondel. Det femte mätbruselementet däremot har en standardavvikelse som är satt till en funktion av höjdderivatan och farten. Funktionen är helt enkelt en skalad summa av uttrycket för beräkning av tippvinkel enligt ekv (25) differentierat med avseende på höjdderivatan och farten. Funktionen är satt till

$$f(\dot{h}, v) = 5 \cdot \left|\frac{\partial\theta_{ref}}{\partial\dot{h}}\right| + 50 \cdot \left|\frac{\partial\theta_{ref}}{\partial v}\right| \quad (37)$$

och ger ett mått på tippvinkelberäkningens känslighet för fel i höjdderivatan och farten. Eftersom felen i attityd och kurs beräknade med hjälp av integrationsrutinen snabbt växer, måste skattade attityd- och kursfel återkopplas tillbaka till integrationsrutinen, vilket utförs med ledning 17. Görs inte detta blir felekvationerna i det andra kalmanfilteret 22 snabbt ogiltiga på grund av att ekvationerna i grund och botten är olinjära. Dessutom återkopplas skattningarna av nollfelen i vinkelhastighetsgyrosignalerna via en ledning 18. Detta medför en bättre linjärisering av det andra kalmanfiltret 22 och dessutom kan sampelfrekvensen f_s hållas nere.

I en del flygsituationer är de beräkningar som utförs i den andra mätrutinen 21 undermåliga, antingen på grund av att mätekvationerna ej är tillräckligt anpassade eller att mätdata i sig är för bristfälliga. Beräkningen av rollvinkeln utifrån luftdata används bara under planflykt. Ingen mätning utnyttjas om vinkelhastigheterna inte är tillräckligt små, typiskt någon grad/sek. Desutom sker en kontroll av mätresidualerna, där mätresidualerna inte tillåts överstiga typiskt en till två gånger tillhörande skattad osäkerhet.

Beteckningar

Koordinatsystem

I (Inertial frame): ett i tröghetsrymden fixt system.

Vid flygning ovanför jordytan är det brukligt att detta systems centrum sammanfaller med jordens centrum. Detta är egentligen en approximation eftersom ett system fixt i tröghetsrymden inte får rotera. Pga att jorden roterar runt solen kommer även I-systemet att rotera. Felet som uppkommer är emellertid försumbart. De accelerationer och vinkelhastigheter som sensorerna i ett tröghetsnavigeringssystem mäter är relativt detta system.

N (Navigation frame): ett system med centrum i flygplanet och med xy-planet hela tiden parallellt med jordytan.

x-axeln pekar mot norr, y-axeln mot öster och z-axeln vertikalt nedåt mot jordytan.

B (Body frame): ett i flygplanet skrovfast system.

Detta koordinatsystem roterar med flygplanet. x-axeln pekar ut genom nosen, y-axeln ut genom högra vingen och z-axeln vertikalt nedåt relativt flygplanet.

Tabell 1 Förklaring av beteckningar för vinklar och vinkelhastigheter. Se också figur 4.

ϕ	Vinkeln mellan y_B och horisontalplanet lutat med vinkeln θ utmed x_B (rollvinkeln).
ϕ_0, $\hat{\phi}$	Begynnelsevärde för rollvinkeln respektive skattad rollvinkel
ϕ_{ref}	Rollvinkeln beräknad med hjälp av data från lftdata och kursderivatan
θ	Vinkeln mellan x_B och horisontalplanet (tippvinkeln).
θ_0, $\hat{\theta}$	Begynnelsevärde för tippvinkeln respektive skattad tippvinkel
θ_{ref}	Tippvinkeln beräknad med hjälp av data från luftdata och anblåsningsgivarna
$\bar{\varphi} = [\phi, \theta]^T$	Komprimerad beteckning av rollvinkeln och tippvinkeln

Tabell 1 Förklaring av beteckningar för vinklar och vinkelhastigheter. Se också figur 4.

$\bar{\varphi}$, $\bar{\varphi}_0$, $\Delta\bar{\varphi}$	Skattad roll- och tippvinkel, skattade begynnelsevärden för roll- och tippvinkeln respektive skillnaden mellan framintegrerad och referensberäknad roll- och tippvinkel
φ_{ref}, φ_{AHRS}	Roll- och tippvinkeln beräknade med hjälp av luftdata och primärdata respektive framintegrerad roll- och tippvinkel där integrationen sker med hjälp av vinkelhastighetsgyrosignalerna
ψ, ψ^i	Vinkeln mellan projektionen av x_B i horisontalplanet och norr (kursvinkeln) respektive tidsdiskret indexering av kursvinkeln
α	Vinkeln mellan luftrelaterad hastighetsvektor projicerad på z-axeln i body frame respektive projicerad på x-axeln i body frame (anfalls-vinkeln)
β	Vinkeln mellan luftrelaterad hastighetsvektor och luftrelaterad hastighetsvektor projicerad på y-axeln i body frame (snedanblåsningsvinkeln)
C_B^N	Transformationsmatris (3 x 3 matris) som transformerar en vektor från body frame (verkligt) till navigation frame. Elementen i denna matris betecknas c_{11}, c_{12}, c_{13}, c_{21}, c_{22}, c_{23}, c_{31}, c_{32}, c_{33} där indexen betecknar rad och kolumn i nämnd ordning
$C_B^N \cdot C_{\hat{B}}^B = C_{\hat{B}}^N = \hat{C}_B^N$	Transformationsmatris som transformerar en vektor från body frame (beräknat) till navigation frame
δC_B^N	Skillnad mellan beräknad och sann C_B^N
$\gamma = (\gamma_x, \gamma_y, \gamma_z)^T$	Vridning kring x-, y- respektive z-axeln i body frame motsvarande felet mellan sant och beräknat body frame
Γ	Antisymmetriska matrisformen av vektorn γ
$\omega_{IB} = \omega = (\omega_x, \omega_y, \omega_z)^T$	Vinkelhastighet kring x-, y- respektive z-axeln i body frame (vinkelhastighetsgyrosignalerna). Dessa vinkelhastighetskomponenter brukar också betecknas med $(p, q, r)^T$
W_{IB}	Vektorn ω_{IB} uttryckt i antisymmetrisk matrisform
$\delta\omega = (\delta\omega_x, \delta\omega_y, \delta\omega_z)^T$	Skillnad mellan verklig och uppmätt vinkelhastighet kring x-, y- respektive z-axeln i body frame
W_{IN}	Rotationen av navigation frame relativt inertial frame som uppstår vid förflyttning över den krökta jordytan. Antisymmetrisk matrisform

Tabell 2 Förklaring av beteckningar för jordmagnetiska fältet.

B_x, B_y, B_z	Jordmagnetiska fältvektorkomponenterna i body frame
$\delta B_x, \delta B_y, \delta B_z$	Skillnaden mellan uppmätta och verkliga fältvektorkomponenter i body frame
B_N, B_B	Jordmagnetiska fältvektorn i navigation frame respektive body frame

Tabell 3 Förklaring av beteckningar som används i samband med filter

$k, k+1$	Används som index och representerar tidpunkten före respektive efter tidsuppdatering
$n, n+1$	Används för att representera nuvarande respektive efterföljande sampel
$-, +$	Används som index och representerar tidpunkten före respektive efter mätuppdatering
x, z, P	Tillståndsvektorn, mätvektorn respektive skattningsosäkerhetsmatrisen
w, Q	Processbrusvektorn respektive kovariansmatrisen för processbruset
A, F	Prediktionsmatrisen i tidskontinuerlig respektive tidsdiskret form
K, H, R	Kalmanförstärkningsmatrisen, mätmatrisen respektive kovariansmatrisen för mätbruset
u_ω, u_b, u_s	Drivande brus för markovprocesserna
$\tau_\omega, \tau_b, \tau_s, \tau, \tau_1, \tau_2$	Tidskonstanter
f_s	Sampelfrekvens

Tabell 4 Förklaring av övriga beteckningar. Se också figur 5.

b_x, b_y, b_z	Bias (nollfel)
s_x, s_y, s_z	Skalfaktorfel
$k_{xy}, k_{xz}, k_{yx}, k_{yz}, k_{zx}, k_{zy}$	Korskopplingsfel (exempelvis står index xy för hur y-komponenten påverkar x-komponenten). Uppkommer pga att axlarna i en triad i verkligheten inte är ortogonala

Tabell 4 Förklaring av övriga beteckningar. Se också figur 5.

$h, \acute{h}$	Höjd respektive lågpassfiltrerad tidsderiverad höjd
v_p, v	Verklig fart relativt luften
g	Gravitationen

PATENTKRAV

1. Metod för att syntetiskt beräkna reservattityd för ett flygplan när flygplanets kurs är känd med hjälp av i flygplanet befintliga data, såsom vinkelhastigheterna p, q, r kring ett skrovfast koordinatsystems (body frame) x-, y- och z- koordinater, luftdatainformation i form av fart, höjd och anfallsvinkel samt kursinformation, **kännetecknad av** att metoden innefattar stegen:
- attityden beräknas med utgångspunkt från de skrovfasta vinkelhastigheterna p, q, r och
- den beräknade attityden korrigeras medelst luftdata och kurs.

2. Metod enligt patentkrav 1, **kännetecknad av** att kursinformationen erhålls från ett kursgyro.

3. Metod enligt patentkrav 1 eller 2, **kännetecknad av** att attityd integreras fram via information om flygplanets skrovfasta vinkelhastigheter (p, q och r) erhållna ur flygplanets skrovfasta vinkelhastighetsgyron.

4. Metod enligt patentkrav 3 , **kännetecknad av** att korrigering av framintegrerad attityd sker med hjälp av attityd beräknad utifrån luftdatainformationen samt kursinformation.

5. Metod för att syntetiskt beräkna reservattityd och reservkurs för ett flygplan med hjälp av i flygplanet befintliga data, såsom vinkelhastigheterna p, q och r kring ett skrovfast koordinatsystems (body frame) x-, y- och z- koordinater och luftdatainformation i form av fart, höjd och anfallsvinkel, **kännetecknad av** att metoden innefattar stegen:
- attityd och kurs beräknas med utgångspunkt från de skrovfasta vinkelhastigheterna p, q och r,
- felen i de uppmätta skrovfasta magnetiska fältvektorkomponenterna skattas,
- de uppmätta skrovfasta magnetiska fältvektorkomponenterna devieras,
- fel i beräknad attityd och kurs skattas med hjälp av luftdata samt devierade uppmätta skrovfasta magnetiska fältvektorkomponenter och
- den beräknade attityden och kursen korrigeras med skattade fel i attityd och kurs.

6. Metod enligt patentkrav 5, **kännetecknad av** att attityd och kurs integreras fram via information om flygplanets skrovfasta vinkelhastigheter (p, q och r) erhållna ur flygplanets skrovfasta vinkelhastighetsgyron.

7. Metod enligt patentkrav 5, **kännetecknad av** att skattning av fel i uppmätta skrovfasta magnetiska fältvektorkomponenter utförs i ett första filter (11).

8. Metod enligt patentkrav 6 eller 7, **kännetecknad av** att i ett andra filter (22) utförs skattning av attitydfel och kursfel som uppkommer vid integration av flygplanets skrovfasta vinkelhastigheter (p, q och r) erhållna ur flygplanets skrovfasta vinkelhastighetsgyron, där skattningen görs med hjälp av attityd beräknad från luftdatainformation samt devierade uppmätta skrovfasta magnetiska fältvektorkomponenter.

9. Metod enligt patentkrav 7 eller 8, **kännetecknad av** att filtreringen sker med hjälp av kalmanfilter.

10. Anordning för att syntetiskt beräkna reservattityd för ett flygplan när flygplanets kurs är känd med hjälp av i flygplanet befintliga data såsom flygplanets skrovfasta vinkelhastigheter (p, q och r), luftdata innefattande åtminstone fart, höjd och anfallsvinkel samt kursinformation, **kännetecknad av** att anordningen innefattar en integrationsrutin (8) för att integrera fram flygplanets attityd ur information om flygplanets skrovfasta vinkelhastigheter (p, q och r) samt att den beräknade attityden korrigeras medelst referensattityd ur luftdata och reservkurs.

11. Anordning enligt patentkrav 10, **kännetecknad av** att kursinformationen erhålls från ett kursgyro.

12. Anordning enligt patentkrav 10 eller 11, **kännetecknad av** att integrationsrutinen (8) integrerar fram flygplanets attityd ur flygplanets skrovfasta vinkelhastigheter (p, q och r) erhållna från flygplanets skrovfasta vinkelhastighetsgyron.

13. Anordning enligt patentkrav 12, **kännetecknad av** att integrationrutinen (8) matas med nollfelskompenserade skrovfasta vinkelhastighetsgyrosignaler.

14. Anordning enligt patentkrav 10, **kännetecknad av** att man med luftdatainformation samt reservkursinformation beräknar en referensattityd.

15. Anordning enligt patentkrav 10, **kännetecknad av** att en syntetiskt genererad korrigerad attityd erhålles genom att en skillnad bildas mellan den ur integrationsrutinen (8) erhållna attityden och en felsignal som representerar felet mellan den integrerade attityden och referensattityden.

16. Anordning för att syntetiskt beräkna reservattityd och reservkurs för ett flygplan med hjälp av i flygplanet befintliga data, såsom uppmätta skrovfasta magnetiska fältvektorkomponenter, flygplanets skrovfasta vinkelhastigheter p, q och r samt luftdata innefattande åtminstone fart, höjd och anfallsvinkel, **kännetecknad av** att anordningen innefattar en första mätrutin (10) som transformerar de uppmätta skrovfasta magnetiska fältvektorkomponenterna till flygplanets navigeringssystem (navigation frame), ett första filter (11) som skattar felen i de beräknade uppmätta skrovfasta magnetiska fältvektorkomponenterna, en integrationsrutin (20) för att integrera fram flygplanets attityd och kurs ur information om flygplanets skrovfasta vinkelhastigheter (p, q och r), ett andra filter (22) för skattning av felen uppkomna i attityd och kurs erhållna vid nämnda integration och en andra mätrutin (21) för beräkning av attityd och kurs ur luftdata och devierade uppmätta skrovfasta magnetiska fältvektorkomponenter.

17. Anordning enligt patentkrav 16, **kännetecknad av** att den första mätrutinen (10) matas med de uppmätta skrovfasta magnetiska fältvektorkomponenterna samt attityd och kurs från flygplanets ordinarie navigeringssystem och transformerar de uppmätta skrovfasta magnetiska fältvektorkomponenterna till flygplanets navigation frame.

18. Anordning enligt patentkrav 17, **kännetecknad av** att det första filtret (11) matas med information från den första mätrutinen (10) och skattar felen i de uppmätta skrovfasta magnetiska fältvektorkomponenterna.

19. Anordning enligt patentkrav 16, **kännetecknad av** att integrationsrutinen (20) integrerar fram flygplanets attityd och kurs ur flygplanets skrovfasta vinkelhastigheter (p, q och r) erhållna från flygplanets skrovfasta vinkelhastighetsgyron.

20. Anordning enligt patentkrav 16, **kännetecknad av** att den andra mätrutinen (21) matas med luftdata, de devierade uppmätta skrovfasta magnetiska fältvektorkomponenterna och med information om flygplanets skrovfasta vinkelhastigheter (p, q och r) och ur dessa värden beräknar en attityd och kurs.

21. Anordning enligt patentkrav 20, **kännetecknad av** att det andra filtret (22) matas med information från den andra mätrutinen (21) och skattar felen i attityd och kurs samt nollfel i skrovfasta vinkelhastighetsgyrosignaler och återstående fel i de uppmätta skrovfasta magnetiska fältvektorkomponenterna för generering av en felsignal.

22. Anordning enligt patentkrav 21, **kännetecknad av** att en syntetiskt genererad korrigerad attityd och kurs erhålles genom att en skillnad bildas mellan
- den ur integrationsrutinen (20) erhållna attityden och kursen och
- felsignalen från det andra filtret (22).

23. Anordning enligt patentkrav 19, **kännetecknad av** att integrationrutinen (20) matas med skrovfasta vinkelhastighetsgyrosignaler kompenserade för skattade nollfel.

24. Anordning enligt något av patentkraven 16 - 23, **kännetecknad av** att det första filtret (11) och/eller det andra filtret (22) utgörs av ett kalmanfilter.

SAMMANDRAG

En metod och en anordning för att syntetiskt beräkna reservattityd och reservkurs medelst i ett flygplan befintliga data. Vid ett utförande finns flygplanets kurs tillgänglig och vid ett annat utförande beräknas kursen utifrån en magnetisk kursgivare. Då kursen är tillgänglig (reservkurs) sker beräkningen av attityd genom sammanvägning av signalerna från vinkelhastighetsgyrona (2) i flygplanets styrsystem, information från luftdata (höjd, fart, anfallsvinkel) samt information om kurs (reservkurs). Då kursen inte är tillgänglig sker beräkningen av attityd och kurs enligt ett utförande med hjälp av kalmanfilter (11, 22) genom sammanvägning av signalerna från vinkelhastighetsgyrona i flygplanets styrsystem, information från luftdata (höjd, fart, anfallsvinkel och snedanblåsningsvinkel) samt information från en i flygplanet befintlig magnetkursdetektor. (Fig. 3).

TENT COOPERATION TREA

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference 893 PCT	FOR FURTHER ACTION	see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.
International application No. PCT/SE 00/00034	International filing date *(day/month/year)* 12 January 2000	(Earliest) Priority Date *(day/month/year)* 18 January 1999
Applicant SAAB AB et al		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. [ ] **Certain claims were found unsearchable** (See Box I).

2. [ ] **Unity of invention is lacking** (See Box II).

3. [ ] The international application contains disclosure of a **nucleotide and/or amino acid sequence listing** and the international search was carried out on the basis of the sequence listing
   - [ ] filed with the international application.
   - [ ] furnished by the applicant separately from the international application,
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   Figure No. 3
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 00/00034

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: G05D 1/08
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: G05D, G01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4914598 A (UWE KROGMANN ET AL), 3 April 1990 (03.04.90), abstract --	1-24
A	US 5841537 A (JAMES H. DOTY), 24 November 1998 (24.11.98), abstract --	1-24
A	WO 9726553 A1 (SEXTANT AVIONIQUE), 24 July 1997 (24.07.97), abstract -- --------	1-24

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
26 May 2000	06-06-2000

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INTERNATIONAL SEARCH REPORT
Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4914598 A	03/04/90	DE 3634023 A	21/04/88
		DE 3775163 A	23/01/92
		EP 0263777 A,B	13/04/88
US 5841537 A	24/11/98	NONE	
WO 9726553 A1	24/07/97	AU 5696596 A	18/11/96
		DE 69603076 D	00/00/00
		EP 0823025 A,B	11/02/98
		EP 0875002 A	04/11/98
		FR 2743892 A,B	25/07/97
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		US 5890884 A	06/04/99

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(71) Applicant *(for all designated States except US)*: SAAB AB [SE/SE]; S-581 88 Linköping (SE).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: ADEBJÖRK, Peter [SE/SE]; Gryningsgatan 73, S-589 29 Linköping (SE). NORDLUND, Per-Johan [SE/SE]; Vretagatan 17, S-582 37 Linköping (SE). CARLSSON, Carl-Olof [SE/SE]; Skogslyckegatan 11 D, S-587 27 Linköping (SE).

(74) Agent: LUNDMARK, Jan-Erik; Saab AB, Patent Department, S-581 88 Linköping (SE).

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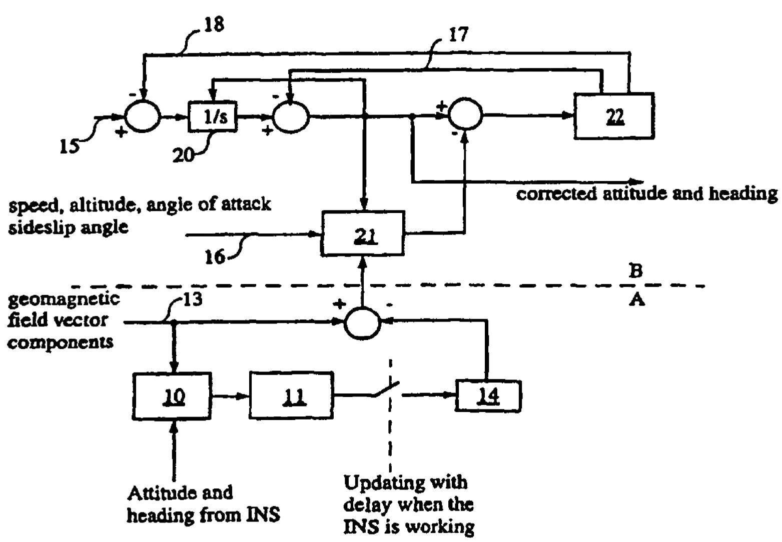

(57) Abstract

A method and an arrangement for synthetically calculating redundant attitude and redundant heading by means of existing data in an aircraft. In one embodiment the heading of the aircraft is available and in another embodiment the heading is calculated from a magnetic heading sensor. When the heading is available (redundant heading) attitude is calculated by weighting together the signals from and angular rate gyros (2) in the aircraft's flight control system, information from air data (altitude, speed, angle of attack) as well as information about heading (redundant heading). When the heading is not available, attitude and heading are calculated in one embodiment with the aid of Kalman filters (11, 22) by weighting together the signals from the angular rate gyros in the aircraft's control system, information from air data (altitude, speed, angle of attack and sideslip angle) as well as information from a magnetic heading detector existing in the aircraft.

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Redundant system for the indication of heading and attitude in an aircraft

TECHNICAL FIELD

The invention relates to a system function which provides display of heading and attitude on displays in an aircraft, for example a head-up display (HUD), in the event of failures in certain equipment for normal attitude display. The system function, which in English is called Attitude and Heading Reference System and is abbreviated AHRS with reference to its initials, supplements the aircraft's normal display for heading and attitude. This display is intended to help the pilot to recover from difficult attitudes and then facilitate return to base/ landing.

PRIOR ART

In order not to lose attitude and heading display in an aircraft in the event of failure of a normally-used inertial navigation system (INS) a redundant system is required. In good visibility a pilot can fly by using the horizon as an attitude reference, but with great uncertainty as to the heading. In bad weather, in cloud and at night when the horizon is not visible, the pilot can easily become disoriented and thereby place the aircraft and him/herself in hazardous situations.

AHRS systems calculate, independently of normal systems, attitude angles (pitch and roll) and heading. Such a system continuously displays the position to the pilot on a display in the cockpit. The need for a redundant system for attitude may be so great that an aircraft is not permitted to fly without one.

Redundant systems in the form of an AHRS unit are available today. Such a unit contains among other things gyros which measure aircraft angle changes in pitch, roll and yaw. It also contains accelerometers and magnetic sensor. The accelerometers are used to establish a horizontal plane. The magnetic sensors are used to obtain a magnetic north end. This type of AHRS system in the form of hardware is costly and involves the installation of heavy, bulky equipment on the aircraft. To overcome this there is proposed in this description a synthetic

AHRS which uses sensors existing in the aircraft, which are not normally intended for AHRS calculation and which therefore partly have significantly lower performance, instead of sensors of the type included in an AHRS unit.

The angles are calculated with the aid of existing sensors in the aircraft. The aim is to use existing angular rate gyro signals and support these with calculations based on other available primary data in the aircraft. Angular rate gyros are normally used in control systems and generally have substantially greater drift than gyros for navigation.

DESCRIPTION OF THE INVENTION

According to one aspect of the invention, a method is provided for synthetically calculating redundant attitude and redundant heading by means of data existing in an aircraft as specified in the claims.

Different forms of embodiment have been developed. In one embodiment the heading of the aircraft is available and in another embodiment the heading is calculated on the basis of a magnetic heading sensor. When the heading is available the calculations can be substantially reduced.

When the heading is available (redundant heading) attitude is calculated by weighting together the signals from the angular rate gyros in the flight control system of the aircraft, information from air data (altitude, speed, angle of attack) and information about heading (redundant heading).

When the heading is not available, attitude and heading are calculated according to one embodiment with the aid of Kalman filters by weighting together the signals from the angular rate gyros in the aircraft's control system, information from air data (altitude, speed, angle of attack and sideslip angle) as well as information from an existing magnetic heading detector in the aircraft.

One advantage of a synthetic AHRS according to the aspect of the invention is that it works out substantially cheaper than conventional AHRS system based on their own sensors if existing sensors in the aircraft can be used. This also saves space and weight in the aircraft.

DESCRIPTION OF FIGURES

Figure 1 shows a schematic diagram of an AHRS function in which the heading is available.

Figure 2 shows the principle for levelling of the attitude of the aircraft in a head-up display, to the left without levelling and to the right with levelling.

Figure 3 shows the block diagram of a redundant system for both attitude and heading.

Figure 4 shows in three pictures the attitude and heading of the aircraft and the axes in the body frame coordinate system, as well as the angle of attack and the sideslip angle.

Figure 5 shows how zero errors and scale factor errors impact the measured value.

DESCRIPTION OF EMBODIMENT

A number of embodiments are described below with the support of the figures. According to the invention, methods are provided for synthetically calculating attitude and heading by means of data existing in the aircraft as specified in the claims.

In a simpler embodiment, the heading of the aircraft is available. In another embodiment the heading is calculated, in this case on the basis of a magnetic heading sensor.

Calculation of AHRS when the heading is known

The signals from the three angular rate gyros 2 rigidly mounted on the body frame are used to determine the orientation of the aircraft relative to the reference coordinate system N (navigation frame). The angular rate gyros 2 measure angular velocities around the three body-frame coordinate axes (x, y, z). The angular velocities are normally designated ω_x or p (rotation around the x-axis), ω_y or q (rotation around the y-axis) and ω_z or r (rotation around the z-axis). The orientation between the body-frame coordinate system B (body) and the N

system is given by the euler angles θ, ϕ and ψ. However, since the heading is known, only θ and ϕ are of interest. With the assumption that the N system is an inertial system and is oriented so that its z-axis is parallel to the g vector of the earth, it can be shown that

$$\begin{bmatrix}\dot{\theta}\\ \dot{\phi}\end{bmatrix} = \begin{bmatrix}\omega_y\cos\phi - \omega_z\sin\phi\\ \omega_x + \tan\theta(\omega_y\sin\phi + \omega_z\cos\phi)\end{bmatrix} \tag{1}$$

If the gyros 2 were ideal, the initial values ϕ_0 and θ_0 were error-free and if the integration method used were accurate, attitude angles can be obtained by solving Eqn (1). In practice, however, none of these preconditions is satisfied; instead, sensor errors etc cause the solution to diverge and relatively soon to become unusable.

Sensor errors in the form of among others zero errors, scale factor errors, misaligned mounting and acceleration-induced drifts constitute the dominant sources of error. In level flight the zero error is the error source that dominates error growth.

Owing to sensor imperfections and uncertainty in initial values, equation (1) gives an estimate of roll and pitch angle derivatives according to

$$\dot{\hat{\bar{\varphi}}} = \begin{bmatrix}\dot{\hat{\theta}}\\ \dot{\hat{\phi}}\end{bmatrix} = \begin{bmatrix}\omega_y\cos\hat{\phi} - \omega_z\sin\hat{\phi}\\ \omega_x + \tan\hat{\theta}(\omega_y\sin\hat{\phi} + \omega_z\cos\hat{\phi})\end{bmatrix} \tag{2}$$

The difference between the expected $\hat{\bar{\varphi}}_{AHRS}$ (calculated by the AHRS function) and the "actual" $\bar{\varphi}_{\mathrm{ref}}$ (from air data, primary data calculated) attitude angles constitutes an estimate of the attitude error

$$\Delta\bar{\varphi} = \hat{\bar{\varphi}}_{AHRS} - \bar{\varphi}_{\mathrm{ref}} \tag{3}$$

See below concerning the use of $\Delta\bar{\varphi}$.

Finally the attitude angles are given as

$$\hat{\bar{\varphi}}_{AHRS} = \int_t \left(\dot{\hat{\bar{\varphi}}}\right) dt + \hat{\bar{\varphi}}_0 - lim(\Delta\bar{\varphi}) \qquad (4)$$

where $\hat{\bar{\varphi}}_0$ constitutes estimated initial values.

Calculation of $\bar{\varphi}_{ref}$

The formula $\theta_{ref} = \arcsin(\dot{h}/v_t) + (\alpha * \cos\phi)$ is used when calculating θ_{ref}. $\dot{h}$ is a high-pass-filtered altitude signal. v_t is true airspeed.

The formula $\phi_{ref} = \arctan(v_t * (\dot{\psi})/g)$ is used when calculating ϕ_{ref}.

$\dot{\psi}$ is a high-pass-filtered heading (redundant heading) signal.

Zero correction of the angular rate gyros

The zero errors in the angular rate gyros 2 are heavily temperature-dependent. It may take 20 to 30 minutes for the gyros to reach operating temperature. This means that an INS failure shortly after take-off might give large zero errors if flying continued. However, it takes a certain time from gyros 2 receiving voltage to the aircraft taking off, which means that part of the temperature stabilisation has been completed when a flight begins. It is also assumed that landing can take place within a short time in the event of an INS failure during takeoff. To minimise zero errors from the angular rate gyros 2 a zero correction of the angular rate gyros is performed by software. This involves comparing the ω (p, q and r) signals from the angular rate gyros 2 with the corresponding signal from the INS, see eqn (5), by generating a difference in 4a. The difference is low-pass-filtered in a filter 5 and added to the angular rate gyro signals in a difference generator 4b, where the signal ω_k which designates the zero-error-corrected gyro signals and is used instead of ω in the AHRS calculations. This is done continuously as long as the INS is working. In the event of an INS failure the most recently performed zero corrections are used for the rest of the flight.

$$\omega_{TNS} = \begin{bmatrix} p_{TNS} \\ q_{TNS} \\ r_{TNS} \end{bmatrix} = \begin{bmatrix} \dot{\phi}_{TNS} - \dot{\psi}_{TNS}\sin\theta_{TNS} \\ \dot{\theta}_{TNS}\cos\phi_{TNS} + \dot{\psi}_{TNS}\cos\theta_{TNS}\sin\phi_{TNS} \\ -\dot{\theta}_{TNS}\sin\phi_{TNS} + \dot{\psi}_{TNS}\cos\theta_{TNS}\cos\phi_{TNS} \end{bmatrix} \tag{5}$$

A block diagram of the realisation of the AHRS function with zero correction of the angular rate gyros is shown in Figure 1. The figure gives a schematic illustration of the AHRS function. The zero correction of the angular rate gyros is performed by the units inside the dashed area D.

ψ_{TNS}, θ_{TNS} and ϕ_{TNS} are high-pass-filtered to obtain $\dot{\psi}_{TNS}$, $\dot{\theta}_{TNS}$ and $\dot{\phi}_{TNS}$. These are used in Eqn (5), which gives ω_{TNS} (p_{TNS}, q_{TNS}, r_{TNS}) in a first block 1. ω (p, q, r) which are obtained as signals from the gyros designated by 2 are low-pass-filtered in a low-pass filter 3, before the difference is generated in 4a.

The difference signal between the ω_{TNS} (p_{TNS}, q_{TNS}, r_{TNS}) signals and the ω (p, q, r) signals is low-pass-filtered with a long time-constant in a low-pass filter 5, ie its mean value is generated over a long time. The filter 5 is initialised at take-off rotation with the shorter time-constant. After a power failure, the filter 5 is initialised instantaneously.

In block 7, $\dot{\hat{\varphi}}$ is calculated, after which the integration according to Equation (4) is performed in an integrator 8, to which the initial conditions $\bar{\varphi}_0$ are added. In a difference generator 9a the signal $\Delta\bar{\varphi}$ is added, but is disconnected by means of a switch 9b under certain changeover conditions, as for example when $|\gamma| > \gamma_{LIM}$ and $|\phi| > \phi_{LIM}$. The $\Delta\bar{\varphi}$ signal passes through a limiter 9c. The magnitude of the output signal from the limiter 9c is dependent on the magnitude of the $\Delta\bar{\varphi}$ signal (ie the input signal to limiter 9c). The $\Delta\bar{\varphi}$ signal is generated according to Equation (3) in a difference generator 9d to which are added calculated $\hat{\bar{\varphi}}_{AHRS}$ attitude angles and "actual" $\bar{\varphi}_{ref}$ attitude angles from sensors (primary data) designated with 9e.

Despite compensations, the calculated angles from the AHRS contain minor zero errors. Since the output signals are used for head-up display, this is corrected by using $\Delta\phi$ in roll and $\Delta\theta$ in

pitch to level the SI image until a stable position is obtained. See Figure 2, where the line H symbolises the actual horizon and where an aircraft is represented by P. Note that this levelling of the HUD only takes place when one is within the limits described above.

AHRS calculation when the heading is also to be calculated

Figure 3 shows schematically the modules that form building blocks for another variant of a synthetic AHRS and how these modules are linked together to create a redundant attitude and a redundant heading.

Figure 3 shows the principle of the redundant system in accordance with the aspect of the invention. The system consists of two subsystems A and B; the first subsystem A performs estimation of any errors in the measured geomagnetic field and the other subsystem B performs calculation of redundant attitude and heading. In all, this results in five building blocks, where a first measurement routine 10 and a first Kalman filter 11 constitute the building blocks in the first subsystem A and further where the integration routine (1/s) 20, measurement routine 21 and a second Kalman filter 22 constitute the building blocks in the second subsystem B.
With measurement routine 10, measured field vector components in the body frame coordinate system are transformed, to a north-, east- and vertically-oriented coordinate system called the navigation frame. The transformation takes place with the aid of attitude and heading from the inertial navigation system of the aircraft, INS, via wire 12. The field vector components of the geomagnetic field are taken from a magnetic heading sensor in the aircraft and arrive via wire 13. In the first Kalman filter 11, the errors in the field vector components are then estimated on the basis of knowledge about the nominal nature of the components, after which the estimated values are stored in a memory 14.

Subsystem A (measurement routine 10 and Kalman filter 11) are used only when the INS is working correctly. In the event of INS failure, the latest possible estimate of the errors in the field vector components is used, ie that which has been stored in memory 14. Since it may be difficult in many cases to decide whether the INS is working as it should, the absolutely last estimate should not be used. In order to solve this, the estimates of errors in the measured

geomagnetic field that are used are at least one flight old. ie the estimates that are stored in the memory from the previous flight or earlier.

The integration routine 20 receives information about angular velocities, in this case for the three coordinate axes x, y and z in the body frame. These are normally designated ω_x or p (rotation around the x-axis), ω_y or q (rotation around the y-axis) and ω_z or r (rotation around the z-axis). The information is taken from the angular rate gyros of the control system and is fed via wire 15 to routine 20 which integrates out attitude and heading via a transformation matrix.

The second measurement routine 21 consists of a developed variant of the first measurement routine 11 and uses the field vector components derived from the first measurement routine 11. In addition, a roll and pitch angle are calculated with the aid of data from existing air data and existing slip sensors, data which arrives to measurement routine 21 via wire 16 to measurement routine 21. By means of the second Kalman filter 22 the attitude and heading errors that arise on integration of the angular rate gyro signals of the control system are primarily calculated. Secondarily, Kalman filter 22 is used to estimate the biases in the angular rate gyros, ie the biases in p, q, and r.

The first measurement routine 10

The geomagnetic field can be calculated theoretically all over the world. To do this, the IGRF (International Geomagnetic Reference Field) is used, for example.
The field vector in the body frame is designated here with B_B and the field vector in the navigation frame with B_N. Further, the three components of the field vector are designated in accordance with

$$B = [B_x, B_y, B_z]^T . \qquad (6)$$

With the aid of the transformation matrix C_B^N, which transforms a vector from body frame to navigation frame, we have

$$B_N = C_B^N \cdot B_B , \qquad (7)$$

where C_B^N has the appearance

$$C_B^N = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \tag{8}$$

The transformation matrix C_B^N is calculated with the aid of attitude and heading, θ, φ, ψ, from the INS.

The difference between a measured field vector and a field vector calculated in accordance with the model will be

$$B_{N,\text{ measured}} - B_{N,\text{ calculated}} = C_B^N \cdot \delta B_B$$

where δ designates the difference between the measured and the calculated quantity.

The left-hand part of Eqn (9) becomes the output signal from the first measurement routine 10 and thus the input signal to Kalman filter 11. Further, the right-hand part of Eqn (9) is used in Kalman filter 11, which is evident from the description of the first Kalman filter 11 below.

The first Kalman filter 11

Given the state model

$$\begin{aligned} x_{k+1} &= F_k x_k + w_k \\ z_k &= H_k x_k + e_k, \end{aligned} \tag{10}$$

a Kalman filter works in accordance with:

Time updating

$$\begin{aligned} x_{k+1}^- &= F_k x_k^+ \\ P_{k+1}^- &= F_k P_k^+ F_k^T + Q_k, \end{aligned} \tag{11}$$

where P_{k+1}^- is the estimated uncertainty of the states after time updating.

Measurement updating

$$\begin{aligned} K_{k+1} &= P^-_{k+1}H^T_{k+1}[H_{k+1}P^-_{k+1}H^T_{k+1}+R_{k+1}]^{-1} \\ x^+_{k+1} &= x^-_{k+1}+K_{k+1}[z_{k+1}-H_{k+1}x^-_{k+1}] \\ P^+_{k+1} &= P^-_{k+1}-K_{k+1}H_{k+1}P^-_{k+1}, \end{aligned} \tag{12}$$

where P^+_{k+1} is the estimated uncertainty of the states after measurement updating.

The errors in the field vector components are modelled according to

$$\begin{bmatrix}\delta B_x\\ \delta B_y\\ \delta B_z\end{bmatrix} = \begin{bmatrix}b_x\\ b_y\\ b_z\end{bmatrix} + \begin{bmatrix}s_x & k_{xy} & k_{xz}\\ k_{yx} & s_y & k_{yz}\\ k_{zx} & k_{zy} & s_z\end{bmatrix} \cdot \begin{bmatrix}B_x\\ B_y\\ B_z\end{bmatrix}, \tag{13}$$

where b are biases, s are scale factor errors and k is a cross-coupling from one component to another (for example, index xy refers to how the y-component affects the x-component). These 12 errors can represent the states in the first Kalman filter 11 according to

$$x_k = \begin{bmatrix}b_x & b_y & b_z & s_x & s_y & s_z & k_{xy} & k_{xz} & k_{yz} & k_{yx} & k_{zx} & k_{zy}\end{bmatrix}^T \tag{14}$$

and each of the state equations looks like this

$$x_{k+1} = x_k + w_k, \tag{15}$$

where the index k designates the time-discrete count-up in time.

In Eqn (15), w_k is a weakly time-discrete process noise to model a certain drift in the errors. Eqn (15) means that the prediction matrix becomes the unit matrix and the covariance matrix for the process noise will be the unit matrix multiplied by σ_w^2, where σ_w is typically set to one hundred-thousandth (dimensionless since the field vector components are normalised to the amount 1 before they are used).

Where measurement updating of Kalman filter 11 is concerned, Eqn (9) is used and the measurement matrix looks like this

$$H_k = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{11}B_x & c_{12}B_y & c_{13}B_z & c_{11}B_y & c_{11}B_z & c_{12}B_z & c_{12}B_x & c_{13}B_x & c_{13}B_y \\ c_{21} & c_{22} & c_{23} & c_{21}B_x & c_{22}B_y & c_{23}B_z & c_{21}B_y & c_{21}B_z & c_{22}B_z & c_{22}B_x & c_{23}B_x & c_{23}B_y \\ c_{31} & c_{32} & c_{33} & c_{31}B_x & c_{32}B_y & c_{33}B_z & c_{31}B_y & c_{31}B_z & c_{32}B_z & c_{32}B_x & c_{33}B_x & c_{33}B_y \end{bmatrix} \tag{16}$$

Owing to unmodelled interference, the measured geomagnetic field vector will deviate from the model, both in direction and in amount. The simplest variant is to model this interference as a constant white measurement noise with the aid of the measurement noise covariance matrix R_k. The standard deviations for the measurement noise for the three field vector component measurements are each typically set to one-tenth (dimensionless because the field vector components are normalised to 1 before they are used).

A Chi2 test is used to avoid the impact of bad measurements. In addition, the measurements of the field vector components are not used if the angular velocities are too high. The reason for this is that various time delays exert an effect at high angular velocities.

Integration routine 20

It can be shown that the time-derivative of the transformation matrix C_B^N becomes

$$\dot{C}_B^N = C_B^N \cdot W_{IB} - W_{IN} \cdot C_B^N . \quad (17)$$

In Eqn (17) W_{IB} and W_{IN} are, respectively, B's (body frame) rotation relative to I (inertial frame) and N's (navigation frame) rotation relative to I. Both are written in matrix form. Since we are concerned with redundant attitude and redundant heading, where the requirements for attitude errors are of the order of 2 degrees, whilst the elements in W_{IN} are of the order of 0.01 degrees, W_{IN} is disregarded. The expression in (17) will then be

$$\dot{C}_B^N = C_B^N \cdot W_{IB} , \quad (18)$$

where W_{IB} is the angular rate gyro signals from the angular rate gyros of the control system. In principle Eqn (18) means that there are nine differential equations. Because of orthogonality, only six of these need be integrated and the other three can be calculated with the aid of the cross-product.

The second measurement routine 21

The second measurement routine 21 consists of a developed variant of the first measurement routine 11, in which the expansion consists of calculating the roll and pitch angles with the aid of data from air data (altitude and speed) and the slip sensors (angle of attack and sideslip angle).

In the first measurement routine 11 it is assumed that only the field vector components are incorrect and that attitude and heading are correct. This assumption is reasonable because the field vector components are resolved with the aid of attitude and heading from the INS. In the second measurement routine 21 this is not satisfied, and consideration must also be given to attitude and heading errors. The field vector used in the second measurement routine is compensated for errors estimated in subsystem A.

Errors in both the field vector and the transformation matrix mean that

$$B_{N,\,Measured} = \hat{C}_B^N \cdot B_{B,\,Measured} \tag{19}$$

where $\hat{C}_B^N$ stands for calculated transformation matrix and means that

$$\hat{C}_B^N = C_B^N + \delta C_B^N. \tag{20}$$

If we use (20), generate the difference between measured and calculated field vector and disregard error products, we get

$$B_{N,\,Measured} - B_{N,\,\mathrm{Calculated}} \approx \delta C_B^N \cdot B_{N,\,\mathrm{Measured}} + \hat{C}_B^N \cdot \delta B_B \ . \tag{21}$$

In the second measurement routine 21, roll and pitch angle are calculated with the aid of altitude, speed, angle of attack and sideslip angle. The pitch angle can be calculated according to

$$\theta_{\mathrm{ref}} = \mathrm{asin}\left(\frac{\dot{h}}{v}\right) + \cos(\phi)\alpha + \sin(\phi)\beta \tag{22}$$

To be able to calculate the pitch angle according to the expression in Eqn (22) an altitude derivative is required. This altitude derivative is not directly accessible and must instead be calculated on the basis of existing altitude which is obtained from air data. The calculation is done according to

$$\dot{h} = \dot{h}(n) = \frac{1}{\tau}\left(\left(\tau - \frac{1}{f_s}\right) \cdot \dot{h}(n-1) + h(n) - h(n-1)\right), \tag{23}$$

ie a high-pass filtering of the altitude. The symbols τ and f_s in Eqn (23) represent respectively the time-constant of the filtering and the sampling frequency. The speed v used in Eqn (22) is approximately v_t (true speed relative to the air). By approximately we mean that, when calculating v_t, measured temperature is not used, which is the normal case, but a so-called standard temperature distribution is used here instead.

Further, the roll angle can be calculated according to

$$\phi_{\text{ref}} = \operatorname{atan}\frac{v\dot{\psi}}{g}. \tag{24}$$

The expression in Eqn (24) applies only for small roll and pitch angles, small angular velocities and moreover when the angles of attack and the sideslip angles are small.

The above two expressions are calculated and compared with the attitude that is calculated via the integration routine by generating the difference according to

$$\begin{aligned} \phi - \phi_{\text{ref}} &= \operatorname{atan}\frac{c_{32}}{c_{33}} - \operatorname{atan}\frac{v(c_{33} \cdot \omega_z + c_{32} \cdot \omega_y)}{g(c_{11}^2 + c_{21}^2)} \\ \theta - \theta_{\text{ref}} &= \operatorname{atan}\frac{-c_{31}}{\sqrt{1 - c_{31}^2}} - \left(\operatorname{asin}\left(\frac{\dot{h}}{v}\right) + \cos\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\alpha + \sin\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\beta\right), \end{aligned} \tag{25}$$

where

$$\begin{aligned} \phi &= \operatorname{atan}\frac{c_{32}}{c_{33}} \\ \theta &= \operatorname{atan}\frac{-c_{31}}{\sqrt{1 - c_{31}^2}} \\ \dot{\psi} &= \frac{c_{33} \cdot \omega_z + c_{32} \cdot \omega_y}{c_{11}^2 + c_{21}^2}. \end{aligned} \tag{26}$$

The second Kalman filter 22

The second Kalman filter 22 can be said to be the heart of the system. Here are estimated the attitude and heading errors that arise on integration of the angular rate gyro signals from the flight control system. Also estimated are the zero errors in the field vector components of the angular rate gyro signals. Further, possible residual errors in the field vector components, ie the errors that the first Kalman filter 11 cannot reach are estimated here. All in all, this means nine states: three for attitude and heading errors, three for the zero errors in the angular rate gyro signals and three for residual errors in the field vector components (three zero errors). Attitude and heading errors are represented by a rotation of the body-frame system from a calculated to a true coordinate system. The error in $\hat{C}_B^N$ can be written

$$\delta C_B^N = \hat{C}_B^N - C_B^N = C_B^N \cdot C_{\hat{B}}^B - C_B^N = C_B^N \cdot (C_{\hat{B}}^B - I) . \tag{27}$$

One can ascertain that

$$C_{\hat{B}}^B = \begin{bmatrix} 1 & -\gamma_z & \gamma_y \\ \gamma_z & 1 & -\gamma_x \\ -\gamma_y & \gamma_x & 1 \end{bmatrix} = \Gamma + I , \tag{28}$$

where Γ is the matrix form of $\gamma = [\gamma_x, \gamma_y, \gamma_z]^T$ and I is the unit matrix (T means transponate).

The elements of the vector γ describe a small rotation around the respective axis between actual (true) and calculated body frame system. The corresponding differential equations for the elements of γ can be derived to

$$\dot{\gamma} = \delta\omega , \tag{29}$$

where $\delta\omega$ is the errors in the angular rates from the angular rate gyros.

The errors in the angular rates are modelled as three first-order Markov processes according to

$$\delta\dot{\omega} = -\frac{1}{\tau_\omega}\delta\omega + u_\omega \tag{30}$$

where the time-constant τ_ω is set typically to a number of hours and the three u_ω to typically less than one degree/second.

Residual errors in the field vector components are modelled (the zero errors) in a similar way, ie

$$\dot{b} = -\frac{1}{\tau_b}b + u_b \tag{31}$$

where τ_b is set typically to a number of hours, and u_b is set typically to a few hundredths (dimensionless because the field vector components are normalised to 1 before they are used).

This gives a state vector according to

$$x_k = \begin{bmatrix}\gamma_x\ \gamma_y\ \gamma_z\ \delta\omega_x\ \delta\omega_y\ \delta\omega_z\ b_x\ b_y\ b_z\end{bmatrix}^T \tag{32}$$

and a prediction matrix according to

$$F_k = I + \int_t^{t+\Delta T} A(\tau)d\tau\,, \tag{33}$$

where $A(\tau)$ is the matrix that described the time-continuous state equations as above. The covariance matrix for the process noise Q_k is set to a diagonal matrix. Among other things, u_ω and u_b described above are used as diagonal elements. As regards the diagonal elements linked to the states for attitude and heading errors (the first three), the effects of the scale factor errors in the angular rate gyros are included. These scale factor errors are normally of the order of 2% and can cause major errors in integrated-out attitude and heading at high angular rates.

The measurements are five in number: three derived field vector components and roll and pitch angle calculated from air data. These measurements are obtained by using the relations (21) and (25).

As regards the measurement matrix H_k, relation (21) is used to fill out the three top lines. This results in the three top lines of the matrix having the appearance

$$H_{k,\,1-3} =$$

$$\begin{bmatrix} c_{13}B_y - c_{12}B_z & c_{11}B_z - c_{13}B_x & c_{12}B_x - c_{11}B_y & 0 & 0 & 0 & c_{11} & c_{12} & c_{13} \\ c_{23}B_y - c_{22}B_z & c_{21}B_z - c_{23}B_x & c_{22}B_x - c_{21}B_y & 0 & 0 & 0 & c_{21} & c_{22} & c_{23} \\ c_{33}B_y - c_{32}B_z & c_{31}B_z - c_{33}B_x & c_{32}B_x - c_{31}B_y & 0 & 0 & 0 & c_{31} & c_{32} & c_{33} \end{bmatrix} \tag{34}$$

For the last two lines of H_k Eqn (25) is used, by differentiating the two right-hand parts with respect to all states in the second Kalman filter 22. As a result, the last two lines get the elements (the index designates row and column in that order)

$$h_{41} = 1 - \frac{vg(c_{33}\omega_y - c_{32}\omega_z)(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33} \cdot \omega_z + c_{32} \cdot \omega_y)^2}$$

$$h_{42} = \frac{2vg(-c_{11}c_{13} - c_{21}c_{23})(c_{33}\omega_z + c_{32}\omega_y) - vg\omega_z c_{31}(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33} \cdot \omega_z + c_{32} \cdot \omega_y)^2} - \frac{c_{31}c_{32}}{c_{32}^2 + c_{33}^2}$$

$$h_{43} = \frac{2vg(c_{11}c_{12} + c_{21}c_{22})(c_{33}\omega_z + c_{32}\omega_y) + vg\omega_y c_{31}(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33} \cdot \omega_z + c_{32} \cdot \omega_y)^2} - \frac{c_{31}c_{33}}{c_{32}^2 + c_{33}^2} \tag{35}$$

$$h_{45} = -\frac{vgc_{32}(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33} \cdot \omega_z + c_{32} \cdot \omega_y)^2}$$

$$h_{46} = -\frac{vgc_{33}(c_{11}^2 + c_{21}^2)}{g^2(c_{11}^2 + c_{21}^2)^2 + v^2(c_{33} \cdot \omega_z + c_{32} \cdot \omega_y)^2}$$

and

$$h_{51} = \sin\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\alpha - \cos\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\beta$$

$$h_{52} = \frac{c_{33}}{\sqrt{1 - c_{31}^2}} + \frac{c_{32}c_{31}}{c_{32}^2 + c_{33}^2}\left(-\sin\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\alpha + \cos\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\beta\right) \tag{36}$$

$$h_{53} = -\frac{c_{32}}{\sqrt{1 - c_{31}^2}} - \frac{c_{33}c_{31}}{c_{32}^2 + c_{33}^2}\left(\sin\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\alpha - \cos\left(\operatorname{atan}\frac{c_{32}}{c_{33}}\right)\beta\right).$$

The remaining elements in the fourth and fifth line are zero.

The simplest choice for the covariance matrix for the measurement noise R_k is a diagonal matrix. The first four measurement noise elements have a standard deviation which is set typically to one-tenth. The fifth measurement noise element on the other hand has a standard deviation that is set to a function of the altitude derivative and the speed. The function is quite simply a scaled sum of the expression for calculating pitch angle and according to Eqn (25) differentiated with respect to the altitude derivative and the speed. The function is set to

$$f(\dot{h}, v) = 5 \cdot \left|\frac{\partial\theta_{\text{ref}}}{\partial\dot{h}}\right| + 50 \cdot \left|\frac{\partial\theta_{\text{ref}}}{\partial v}\right| \tag{37}$$

and gives a measure of the sensitivity of the pitch angle calculation to errors in the altitude derivative and the speed.

Since the errors in attitude and heading calculated with the aid of the integration routine grow rapidly, estimated attitude and heading errors must be fed back to the integration routine,

which is done with wire 17. If this is not done, the error equations in the second Kalman filter 22 rapidly become invalid by reason of the fact that the equations are fundamentally non-linear. In addition, the estimates of the zero errors in the angular rate gyros are fed back via a wire 18. This results in better linearisation of the second Kalman filter 22 and furthermore the sampling frequency f_s can be kept down.

In some flying situations the calculations that are performed in the second measurement routine 21 are inferior, either because the measurement equations are not sufficiently matched or because the measurement data is inherently poor. Calculation of the roll angle from air data is used only in level flight. No measurement is used if the angular rates are not sufficiently small, typically a couple of degrees or so per second. The measurement residuals are also checked, where the measurement residuals are not allowed to exceed typically one to two times the associated estimated uncertainty.

Symbols

Coordinate systems

I (Inertial frame): a system fixed in inertial space.
When flying above the surface of the earth it is customary for the centre of this system to coincide with the centre of the earth. This is really an approximation, since a system fixed in inertial space must not rotate. Because the earth rotates around the sun, the I-system will also rotate. However, the error that arises is negligible. The accelerations and angular rates measured by the sensors in an inertial navigation system are relative to that system.
N (Navigation frame): a system with its centre in the aircraft and with its xy plane always parallel to the surface of the earth.
The x-axis points to the north, the y-axis to the east and the z-axis vertically down towards the surface of the earth.
B (Body frame): a system in the aircraft, fixed to the body frame.
This coordinate system rotates with the aircraft. The x-axis points out through the nose, the y-axis through the starboard wing and the z-axis vertically down relative to the aircraft.

Table 1 Explanation of designations (symbols) for angles and angular rates. See also Figure 4.

ϕ	Angle between y_B and the horizontal plane, tilted by the angle θ along x_B (roll angle).
ϕ_0, $\hat{\phi}$	Initial value for the roll angle and estimated roll angle, respectively
ϕ_{ref}	Roll angle calculated with the aid of data from air data and the heading derivative
θ	Angle between x_B and the horizontal plane (pitch angle).
θ_0, $\hat{\theta}$	Initial value for the pitch angle and estimated pitch angle, respectively
θ_{ref}	Pitch angle calculated with the aid of data from air data and the slip sensors
$\bar{\varphi} = [\phi, \theta]^T$	Compressed symbol for roll angle and pitch angle
$\hat{\bar{\varphi}}$, $\hat{\bar{\varphi}}_0$, $\Delta\bar{\varphi}$	Respectively: estimated roll and pitch angle, estimated initial values for roll and pitch angle and difference between integrated-out and reference-calculated roll and pitch angle
φ_{ref}, φ_{AHRS}	Respectively: roll and pitch angle calculated with the aid of air data and primary data, and integrated-out roll and pitch angle, where integration is done with the aid of the angular rate gyro signals
ψ, ψ^i	Respectively: angle between the projection of x_B in the horizontal plane and north (heading angle), and discrete indexing of heading angle
α	Angle between air-related rate vector projected on the z-axis in body frame and projected on the x-axis in body frame (angle of attack)
β	Angle between air-related velocity vector and air-related velocity vector projected on the y-axis in body frame (sideslip angle)
C_B^N	Transformation matrix (3 x 3 matrix) which transforms a vector from body frame (actual) to navigation frame. The elements of this matrix are designated c_{11}, c_{12}, c_{13}, c_{21}, c_{22}, c_{23}, c_{31}, c_{32}, c_{33}, where the index designates row and column in that order
$C_B^N \cdot C_{\hat{B}}^B = C_{\hat{B}}^N = \hat{C}_B^N$	Transformation matrix which transforms a vector from body frame (calculated) to navigation frame

Table 1 Explanation of designations (symbols) for angles and angular rates. See also Figure 4.

δC_B^N	Difference between calculated and true C_B^N
$\gamma = (\gamma_x, \gamma_y, \gamma_z)^T$	Rotation around, respectively, the x-, y- and z-axis in body frame, corresponding to the error between true and calculated body frame
Γ	Anti-symmetrical matrix form of the vector γ
$\omega_{IB} = \omega = (\omega_x, \omega_y, \omega_z)^T$	Angular rate around, respectively, the x-, y- and z-axis in body frame (angular rate gyro signals). These angular rate components are customarily also designated $(p, q, r)^T$
W_{IB}	The vector ω_{IB} expressed in anti-symmetrical matrix form
$\delta\omega = (\delta\omega_x, \delta\omega_y, \delta\omega_z)^T$	Difference between actual and measured angular rate around, respectively, the x-, y- and z-axis in body frame
W_{IN}	Rotation of navigation frame relative to inertial frame that occurs when moving over the curved surface of the earth. Anti-symmetrical matrix form

Table 2 Explanation of symbols for the geomagnetic field.

B_x, B_y, B_z	Geomagnetic field vector components in body frame
$\delta B_x, \delta B_y, \delta B_z$	Difference between measured and actual field vector components in body frame
B_N, B_B	Geomagnetic field vector in navigation frame and body frame, respectively

Table 3 Explanation of symbols used in connection with filters

$k, k+1$	Used as an index, and represent the instant before and after time updating, respectively
$n, n+1$	Used to represent the present and subsequent sample, respectively
-, +	Used as an index, and represent the instant before and after measurement updating, respectively
x, z, P	State vector, measurement vector and estimate uncertainty matrix
w, Q	Process noise vector and covariance matrix for process noise, respectively

Table 3 Explanation of symbols used in connection with filters

A, F	Prediction matrix in time-continuous and time-discrete form
K, H, R	Kalman gain matrix, measurement matrix and covariance matrix for measurement noise, respectively
u_ω, u_b, u_s	Driving noise for the Markov processes
τ_ω, τ_b, τ_s, τ, τ_1, τ_2	Time-constants
f_s	Sampling frequency

Table 4 Explanation of other symbols. See also Figure 5.

b_x, b_y, b_z	Bias (zero errors)
s_x, s_y, s_z	Scale factor errors
k_{xy}, k_{xz}, k_{yx}, k_{yz}, k_{zx}, k_{zy}	Cross-connection errors (for example, index xy stands for how the y-component affects the x-component). Arise because the axes in triad are not truly orthogonal.
h, $\dot{h}$	Altitude and low-pass-filtered time-derived altitude respectively
v_t, v	True speed relative to the air
g	Gravity

CLAIMS

1. Method for synthetically calculating redundant attitude for an aircraft when the heading of the aircraft is known, with the aid of data existing in the aircraft, such as the angular rates p, q, r around the x-, y- and z- coordinates of an aircraft-fixed (body frame) coordinate system, air data information in the form of speed, altitude and angle of attack as well as heading information, **characterised in that** the method includes the steps:
- attitude is calculated on the basis of the aircraft-fixed angular rates p, q, r and
- the calculated attitude is corrected by means of air data and heading.

2. Method according to claim 1, **characterised in that** the heading information is obtained from a heading gyro.

3. Method according to claim 1 or 2, **characterised in that** attitude is integrated out via information about the body-frame angular rates (p, q and r) obtained from the aircraft-fixed angular rate gyros of the aircraft.

4. Method according to claim 3, **characterised in that** correction of the integrated-out attitude takes place with the aid of attitude calculated on the basis of air data information and heading information.

5. Method for synthetically calculating redundant attitude and redundant heading for an aircraft with the aid of data existing in the aircraft, such as the angular rates p, q, r around the x-, y- and z- coordinates of an aircraft-fixed (body frame) coordinate system, air data information in the form of speed, altitude and angle of attack, **characterised in that** the method includes the steps:
- attitude and heading are calculated on the basis of the body-frame angular rates p, q, r
- the errors in the measured body-frame magnetic field vector components are estimated,
- the measured body-frame field magnetic field vector is derived,
- errors in calculated attitude and heading are estimated with the aid of air data and derived measured body-frame magnetic field vector components and
- the calculated attitude and heading are corrected by means of estimated errors in attitude and heading.

6. Method according to claim 5, **characterised in that** attitude andr heading are integrated out via information about the aircraft's body-frame angular rates (p, q and r) obtained from the aircraft's body-frame angular rate gyros.

7. Method according to claim 5, **characterised in that** estimation of errors in measured body-frame magnetic field vector components is performed in a first filter (11).

8. Method according to claims 6 or 7, **characterised in that** in a second filter (22) is performed estimation of attitude errors and heading errors that arise on integration of the aircraft's body-frame angular rates (p, q and r) obtained from the aircraft's body-frame angular rate gyros, where the estimation is done with the aid of attitude calculated from air data information as well as derived measured body-frame magnetic field vector components.

9. Method according to claims 7 or 8, **characterised in that** the filtering takes place with the aid of Kalman filters.

10. Arrangement for synthetically calculating redundant attitude for an aircraft when the aircraft's heading is known, with the aid of data existing in the aircraft such as the aircraft's body-frame angular rates (p, q and r), air data including at least speed, altitude and angle of attack as well as heading information, **characterised in that** the arrangement includes an integration routine (8) to integrate out the aircraft's attitude from information about the aircraft's body-frame angular rates (p, q and r) as well as that the calculated attitude is corrected by means of reference attitude from air data and redundant heading.

11. Arrangement according to claim 10, **characterised in that** the heading information is obtained from a heading gyro.

12. Arrangement according to claim 10 or 11, **characterised in that** integration routine (8) integrates out the aircraft's attitude from the aircraft's body-frame angular rates (p, q and r) obtained from the aircraft's body-frame angular rate gyros.

13. Arrangement according to claim 12, **characterised in that** the integration routine (8) is fed with the zero-error-compensated body-frame angular rate gyro signals.

14. Arrangement according to claim 10, **characterised in that** a reference attitude is calculated with air data information as well as redundant heading information.

15. Arrangement according to claim 10, **characterised in that** a synthetically-generated corrected attitude is obtained by generating a difference between the attitude obtained from the integration routine (8) and an error signal that represents the error between the integrated attitude and the reference attitude.

16. Arrangement for synthetically calculating redundant attitude and redundant heading for an aircraft with the aid of data existing in the aircraft such as measured body-frame field vector components, the aircraft's body-frame angular rates (p, q and r) as well as air data including at least speed, altitude and angle of attack, **characterised in that** the arrangement includes a first measurement routine (10) which transforms the measured body-frame magnetic field vector components to the aircraft's navigation system (navigation frame), a first filter (11) which estimates the errors in the calculated measured body-frame field vector components, an integration routine (20) for integrating out the aircraft's attitude and heading from information about the aircraft's body-frame angular rates (p, q and r), a second filter (22) for estimating the errors arising in attitude and heading obtained in the said integration and a second measurement routine (21) for calculating attitude and heading from air data and derived measured body-frame magnetic field vector components.

17. Arrangement according to claim 16, **characterised in that** the first measurement routine (10) is fed with the measured body-frame magnetic field vector components, as well as attitude and heading from the aircraft's normal navigation system and transforms the measured body-frame magnetic field vector components to the aircraft's navigation frame.

18. Arrangement according to claim 17, **characterised in that** the first filter (11) is fed with information from the first measurement routine (10) and estimates the errors in the measured body-frame magnetic field vector components.

19. Arrangement according to claim 16, **characterised in that** the integration routine (20) integrates out the aircraft's attitude and heading from the aircraft's body-frame angular rates (p, q and r) obtained from the aircraft's body-frame angular rate gyros.

20. Arrangement according to claim 16, **characterised in that** the second measurement routine (21) is fed with air data, the derived measured body-frame magnetic field vector components and with information about the aircraft's body-frame angular rates (p, q and r) and from these values calculates an attitude and a heading.

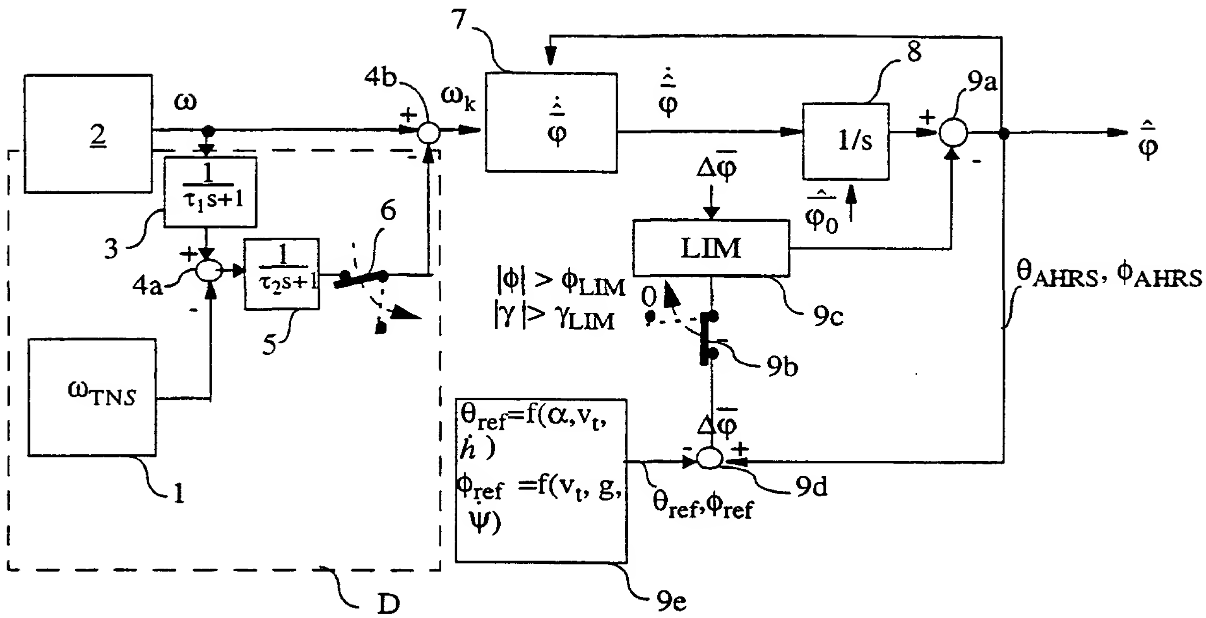
21. Arrangement according to claim 20, **characterised in that** the second filter (22) is fed with information from the second measurement routine (21) and estimates the errors in attitude and heading as well as zero error in body-frame angular rate gyro signals and residual errors in the measured body-frame magnetic field vector components for generating an error signal.

22. Arrangement according to claim 21, **characterised in that** a synthetically-generated corrected attitude and heading are obtained by generating a difference between
- the attitude obtained from the integration routine (20) and heading and
- the error signal from the second filter (22).

23. Arrangement according to claim 19, **characterised in that** the integration routine (20) is fed with body-frame angular rate gyro signals compensated for estimated zero errors.

24. Arrangement according to any of claims 16 - 23, **characterised in that** the first filter (11) and/or the second filter (22) consists of a Kalman filter.

Fig. 1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ω
4b
ω_k
7
8
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1/s
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$\Delta\bar{\varphi}$
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LIM
$\frac{1}{\tau_1 s+1}$
3
4a
$\frac{1}{\tau_2 s+1}$
6
5
$|\phi| > \phi_{LIM}$
$|\gamma| > \gamma_{LIM}$
9c
9b
$\theta_{AHRS}, \phi_{AHRS}$
ω_{TNS}
1
$\theta_{ref}=f(\alpha,v_t, \dot{h})$
$\phi_{ref} =f(v_t, g, \psi)$
θ_{ref},ϕ_{ref}
9d
9e
D

Fig. 2

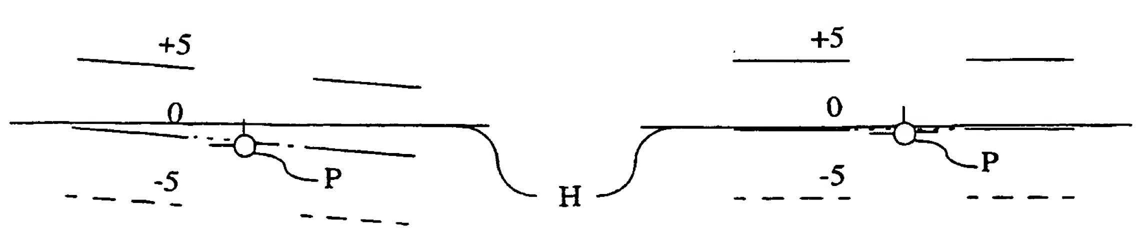
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Fig. 3

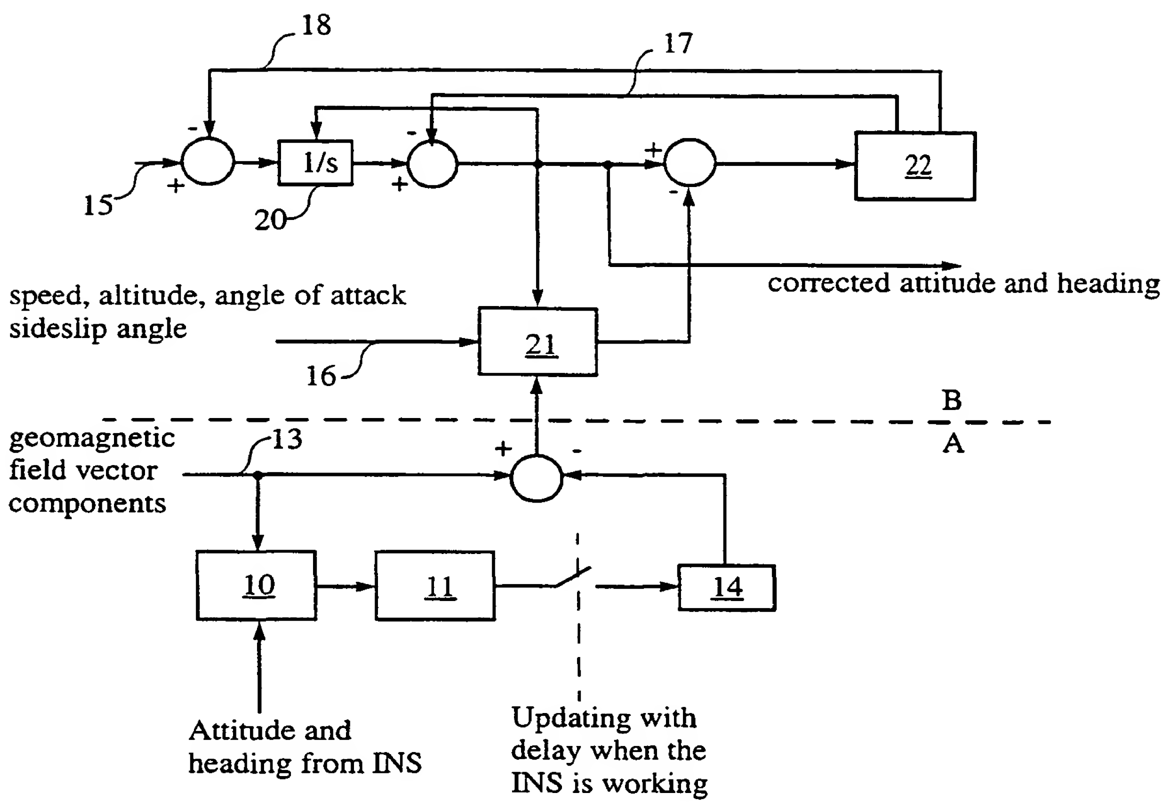
18
17
15
20
1/s
22
corrected attitude and heading
speed, altitude, angle of attack
sideslip angle
16
21
B
A
geomagnetic
field vector
components
13
10
11
14
Attitude and
heading from INS
Updating with
delay when the
INS is working

Fig. 4

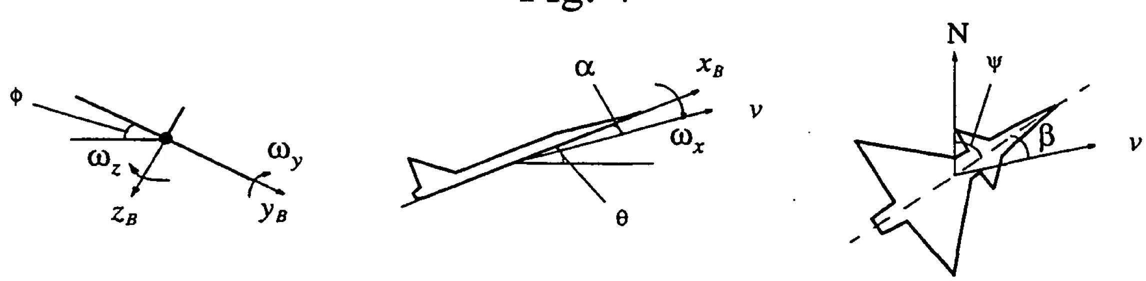
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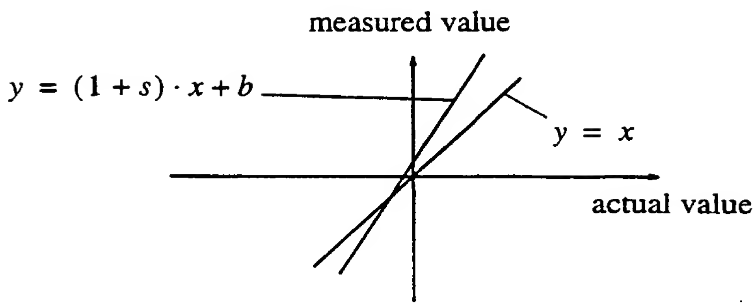
Fig. 5



INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 00/00034

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: G05D 1/08
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: G05D, G01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4914598 A (UWE KROGMANN ET AL), 3 April 1990 (03.04.90), abstract --	1-24
A	US 5841537 A (JAMES H. DOTY), 24 November 1998 (24.11.98), abstract --	1-24
A	WO 9726553 A1 (SEXTANT AVIONIQUE), 24 July 1997 (24.07.97), abstract -- --------	1-24

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
26 May 2000	06-06-2000
Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Authorized officer Gunnel Wästerlid/mj Telephone No. +46 8 782 25 00

INTERNATIONAL SEARCH REPORT

Information on patent family members

02/12/99

International application No.

PCT/SE 00/00034

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4914598 A	03/04/90	DE 3634023 A	21/04/88
		DE 3775163 A	23/01/92
		EP 0263777 A,B	13/04/88
US 5841537 A	24/11/98	NONE	
WO 9726553 A1	24/07/97	AU 5696596 A	18/11/96
		DE 69603076 D	00/00/00
		EP 0823025 A,B	11/02/98
		EP 0875002 A	04/11/98
		FR 2743892 A,B	25/07/97
		JP 11504096 T	06/04/99
		US 5890884 A	06/04/99